Internet of Things

Abdul Salam

Internet of Things for Sustainable Community Development

Wireless Communications, Sensing, and Systems

Springer

Internet of Things

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This book is dedicated to Umbreen, Alizay, Anzalna, *and* Naba.

Preface

Fires in Amazon rainforest, Hurricane Dorian in Bahamas, and wildfires in California are among some of the recent events related to the climate change. The rising sea levels, higher temperatures, and extreme precipitation are some of the causation of climate change. The communities around the world are coping with these changes now. In this regard, an untypical effort from all sectors of community is needed to address critical problems of adapting to climate change and feeding 7.7 billion people.

The *Internet of Things for Sustainable Community Development* addresses the key inter-related environmental, climate change, energy, water, health, mining, agro-economic, and cybersecurity challenges that limit the development of sustainable and resilient society. The aim of this book is to present an integrated depiction of how the Internet of Things "IoT" can stimulate the sustainable community development. The expertise across multiple domains including engineering and technology, ecosystems and natural resource management, environmental toxicology, human health, agriculture, mining, and urban underground infrastructure monitoring is introduced to examine important environmental challenges that can be solved with applications of recent advancements in Internet of Things.

In these domains, the sensing data is generated by a wide range of sensors, from point-based direct in situ measurements to airborne and remote sensing for global coverage through satellites. In each domain, the sensing requirements change considerably, stretching from plant level water status to field level soil moisture, and regional level cloud hydrometer to global scale climate crises and greenhouse gases. The integration of huge volumes of data being generated across these spatial–temporal scales is a major challenge. Moreover, the transmission and processing of this data in decision support systems to address sustainability challenges requires cross-disciplinary endeavors with expertise in sensing, wireless communications, systems science, and modeling, in addition to the specific domain knowledge. The Internet of Things has strong potential to foster the creation of these cross-disciplinary next-generation sensing and communication systems using IoT. These IoT systems for data gathering, wireless communications, processing, and presentation of sensing data are vital to get insights into the biological, physical, and

chemical processes in the environment, and forecasting the prospective advancement of ecosystems sustainability. Such forecasts are also required to support policy and regulation decisions.

The *Internet of Things for Sustainable Community Development* presents a portfolio of cutting-edge, interdisciplinary research developments and challenges in IoT sensing, communications, and systems. It provides a well-founded coverage of these technologies with rigorous focus on scientific concepts, evolution, and applications to sustainability. The comprehensive contents are arranged systemically to provide the scientific foundations of Internet of Things for sustainable community development. The book covers research and innovation ecosystem of the Internet of Things for sustainability in the following major areas that are explored in this book. These areas highlight converging activities that enable the main cohesive objective of sustainable community development.

- Climate Change
- Sustainable Energy Systems
- Sustainable Water
- Human Health
- Sustainable Mining
- Decision Agriculture
- Storm and Wastewater
- Sustainable Forestry

Each of these areas emphasizes core IoT research challenges and solutions while leveraging their shared traits, interdependencies, and expertise to converge on applications of IoT to sustainability challenges. These sections of our community do not exist in segregation. The energy and water are fully intertwisted because the water is used to produce energy, and the energy is needed to drain, remedy, and transport water, which underscores the connection between the water-dependent crop growers and city dwellers. Moreover, the human health is impacted by water availability and quality, energy availability, cultivation, mining, and waste management, inter alia, impacting patients, diseases spread, and outbreak. Furthermore, forestry and watershed are impacted by water availability, energy supply, climate crisis, and biodiversity.

In that regard, the book emphasizes IoT paradigm's sensing, wireless communications, monitoring, actuation, and real-time decision capabilities for sustainability "things". Thus, proper focus is also given to systems, standards, and tools that have tremendous potential to achieve United Nations Sustainable Development Goals. It provides a comprehensive reference to all these aspects in an easy language that is understandable by a wide audience. It also includes advanced treatment of sustainability IoT technology applications and provides in-depth coverage of research developments and open research challenges.

While intended primarily for sustainable engineering and technology professionals, researchers, and students, this book is also beneficial to policy makers, city planners and managers, technicians, and industry professionals. The research in Internet of Things for sustainability has a vital role to play in shaping the future of

our community as they must create a research and education ecosystem promoting impactful solutions-oriented science to help citizenry, government, industry, and other stakeholders work collaboratively to make informed, socially responsible, science-based decisions. The socio-technical analysis presented in this monograph together with application of the latest innovations in IoT sensing, systems, and wireless communications technologies allows for a deeper understanding and management of these complex interconnected human-socio-environmental challenges.

West Lafayette, IN, USA
October 2019

Abdul Salam

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Contents

About the Author

Abdul Salam received the B.Sc. and M.S. degrees in computer science from Bahauddin Zakariya University, Multan, Pakistan, in 2001 and 2004, respectively, the M.S. degree in computer engineering from UET, Taxila, Pakistan, in 2012, and the Ph.D. degree in computer engineering from the Department of Computer Science and Engineering, University of Nebraska, Lincoln, NE, USA. He was a Lecturer with the Department of Computer Science, Bahauddin Zakariya University, and the Department of Computer Science and Information Technology, Islamia University, Bahawalpur, Pakistan. He is currently an Assistant Professor with the Department of Computer and Information Technology, Purdue University, West Lafayette, IN, USA. His current research interests are in the areas of sustainability, sensing, wireless networking, and Internet of Things (IoT). Abdul Salam is a Member of the Realizing the Digital Enterprise research group and Center for the Environment (C4E), a Purdue's initiative for interdisciplinary, problem-driven research and teaching. He was a recipient of the ICCCN 2016 Best Paper Award, and the Robert B. Daugherty Water for Food Institute Fellowship. He served in the Pakistan Army for 9 years in a number of command, staff, and field roles. He held the principal position at the Army Public School and College, Thal Cantonment. He is the Director of the Environmental Networking Technology Laboratory. He has served as an Associate Editor for the IEEE GRSS Remote Sensing Code Library from 2016 to 2018. He is an Associate Editor of the *Advanced Electromagnetics Journal* and *Array* (Elsevier).

Chapter 1
Internet of Things for Sustainable Community Development: Introduction and Overview

Abstract The two-third of the city-dwelling world population by 2050 poses numerous global challenges in the infrastructure and natural resource management domains (e.g., water and food scarcity, increasing global temperatures, and energy issues). The IoT with integrated sensing and communication capabilities has the strong potential for the robust, sustainable, and informed resource management in the urban and rural communities. In this chapter, the vital concepts of sustainable community development are discussed. The IoT and sustainability interactions are explained with emphasis on Sustainable Development Goals (SDGs) and communication technologies. Moreover, IoT opportunities and challenges are discussed in the context of sustainable community development.

1.1 Introduction

The sustainability is one of the vital factors in realization of the digital future. The Internet of Things (IoT) is envisaged as one of the enabling paradigms of this sustainable digital transformation and community development. In this book, the community is referred as any geographical zones that function under some sort of structure and resources at its disposal to meet their current and future needs. The community sustainability depends on risk tolerance. The combined economic value of the industrial IoT along with public and consumer sector is likely to be more than $15 trillion by 2030 [28, 67, 71]. Moreover, the convergence of the IoT with other technologies (e.g., artificial intelligence (AI), technological revolution, blockchain, cluster and cloud computing) presents a tremendous potential for sustainable community development.

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1.1.1 Global Efforts to Address Sustainability

A United Nations conference on the human environment was held in Stockholm, Sweden in 1992. It was the first conference to discuss environmental issues. A report titled "Our Common Future" (also referred to as Brundtland report [38]) published by World Commission on Environment and Development defined sustainability as:

> "development that meets the needs of the present without compromising the ability of future generations to meet their own needs"

This report played an important role in increasing the awareness of environmental sustainable development. It identified many issues and changed our thinking towards the sustainability. Accordingly, the United Nations started developing indicators and systems for sustainable development. Since then many conferences are held for sustainable development. The progress made these conferences is outlined below:

- In 1983, the General Assembly (resolution 38/161) established a special commission to report on strategies for sustainable development, environment, and the global problems by 2000. The commission was later renamed to World Commission on Environment and Development.
- Earth Summit, United Nations Conference on Environment and Development (UNCED), June 1992. Approximately, 100 heads of state met in this Earth Summit to discuss pressing problems in environmental protection and socio-economic sustainable development.
- Barbados Programme of Action (BPOA). UN General Assembly resolution 47/189. UN Global Conference on the Sustainable Development of SIDS, Barbados, 1994. A 14-point program identified priority areas recommended actions.
- A UN General Assembly review session was held to review progress of sustainable development in New York, USA in 1997.
- World Summit on Sustainable Development (WSSD). The Johannesburg summit was held in 2002 to address challenges in improving human lives, natural resources conservation, increasing water, sanitation, energy, food, shelter, and health.
- Mauritius Strategy of Implementation (MSI 2005). It was held in Port Louis, Mauritius to review sustainability progress in 2005.
- MSI+5. It was held in New York, USA in 2010 to review Mauritius Strategy of Implementation.
- The UN Conference on Sustainable Development (Rio+20) in Rio de Janeiro, Brazil, in June 2012. It was decided to develop a set of Sustainable Development Goals (SDGs) on top of the millennium development goals (MDGs).

Fig. 1.1 The UN Sustainable Development Goals [41]

1.1.2 Sustainable Development Goals (SDGs)

In 2015, UN General Assembly set forth the Sustainable Development Goals (SDGs) in its resolution 70/1 with 2030 [71] as the target year [66]. These goals have been developed with the community involvement including academia, governments, and private sector. It encompasses three major sustainable community development dimensions (e.g., protection of the environment, social diversity and inclusions, and economic growth). The SDGs have become the widely accepted and adopted standard system to attain the aim of sustainable community development. These goals are important in the entire IoT paradigm to increase the sustainability and social impact. The UN Sustainable Development Goals are shown in Fig. 1.1. The IoT with its ability to sense and communicate through interconnection of things and systems in different environments has the great benefit of achieving these sustainable development goals. In the sustainability area, the IoT along with technology is going to be a huge game changer in the near future. It is a comprehensive, commercially viable, widely available and accepted technology to achieve these goals with many social and economic benefits at the regional and national level to broader community.

1.1.3 Sustainability Indicators

The indicators of sustainability are useful to describe minimum and contemporary requirements for sustainability. Accordingly, management policies and actions can be evaluated to make a reliable forecast of future changes.

> "indicators must provide information relevant to specific assessment questions, which are developed to focus monitoring data on environmental management issues."—Evaluation Guidelines for Ecological Indicators [37].

The sustainability indicators alone cannot help to achieve sustainable goals. More detailed actions are required at appropriate levels coupled with policy decisions. For example, surface water quality indicators only provide information about issues only at a small spatial and temporal scale requiring extrapolation for decision making. Accordingly, the sustainable development guides policies considering all these factors. In the next section, the potential of the IoT as a comprehensive enabling paradigm to achieve SDGs is discussed.

1.2 IoT as Enabling Paradigm for Sustainability

The Internet of Things (IoT) for sustainable community development is envisaged to develop the engineered systems that enable sustainability by protecting the natural and environmental systems [14, 16]. Through interconnection of systems, sensing and communication technologies, IoT for sustainability aims to provide a paradigm that balance community's need to provide ecological and environmental protection, and maintains secure economic society.

The strong relationship between the Internet of Things and sustainability cannot be overemphasized [9, 25, 32, 35, 59, 60, 65, 67, 68, 72]. For example, a flood, sewerage, and storm overflow monitoring [53] Internet of Things solution based on sensing and communications supports sustainable communities (SDG 11) by reducing water related disasters and economic losses. An IoT for condition based maintenance of smart grid supports infrastructure (SDG 9). A city-scale smart lighting IoT supports improvements in energy efficiency (SDG 7). The next-generation wireless IoT has the potential of advancements in multiple fronts to accommodate the ever-increasing demands of commercial applications, scientific infrastructures, governmental agencies, and public, in general; for better and larger-scale connectivity (SDG 9). In the area of human health (SDG 3), instead of a single major technological breakthrough the community can rely on the culmination of several key enabling IoT technologies. The wireless data harvesting IoT technologies can provide managers and users real-time access to crop and soil moisture data, which supports effective water management decision making (SDG 2 and 12). In digital forest management, the early warning system for drought stress can help to initiate and prioritize actions (SDG 13). The forest soil moisture detection can guide restoration decisions. These examples clearly show that sustainable community development is the mainstream benefit of Internet of Things.

In a study [28], the relationship between the Internet of Things and sustainability has been explored. Particularly, the 640 different Internet of Things projects were compared with the 17 SDGs in order to analyze the relationship between sustainability and Internet of Things. It has been shown that 84% of the analyzed IoT projects exhibited stronger potential to attain these goals. The five SDGs (SDG# 3, 7, 9, 11, and 12) were emphasized by 75% of the projects. The IoT supports sustainable development in following areas:

- Ecological Engineering. The IoT enables sustainable development in the area ecological engineering (e.g., rehabilitating and enhancement of ecological functions to natural systems and natural capital) [60].
- Earth Systems Engineering. The sustainable development of IoT supports monitoring of earth systems (e.g., greenhouse gas emissions). It has strong potential to guide adaption to varying climate, forestry, mining, energy systems, and related global scale concerns through development of decision support systems [42].
- Industrial Ecology. The IoT fosters advancements and innovations in the area of industrial ecology, including evolution of life cycle assessment and economic models, and measurements for sustainable systems [84].
- Environmental Sustainability and Green Engineering. The IoT paradigm has great potential to advance the sustainability of infrastructures (e.g., water, recycling and reuse of drinking water, stormwater, waste water, climate assessment) [47]. Accordingly, the IoT guides innovations and growth strategies in distribution and collection systems based on its sensing and monitoring paradigm.

1.3 SDG Goals and Sustainable IoT Systems

The examples of the sustainable IoT systems in developing and developed countries are explained in the following.

1.4 Examples from Developing Countries

In developing and emerging countries the IoT paradigm has the strong potentials to make big improvements in sustainability and human life [28]. With the increasing coverage of wireless networks in developing countries, it has become easier to form IoT networks with interconnection of “things.” The second/third generation wireless/cellular networking infrastructure in emerging countries surpasses than electricity, water, and sewage infrastructure. The adaption of modern technology such as technological innovations in the field of digital agriculture, health, environmental monitoring, energy systems, water resource monitoring, and livestock, is lacking due to lack on basic resources and supporting infrastructure required for technology operation in developed countries. Consequently, the IoT monitoring

systems are either in their infancy or do not exist. Scarce connectivity and spectrum availability are some of the other limiting factors. Therefore, there is need of ubiquitous connectivity with energy efficient, low-cost wireless, machine to machine (M2M), and sensing technologies. Moreover, great potential exists for sustainable community development using IoT in various areas. The prospects for a variety of sustainable IoT use cases are very high. Higher level of efficiency can be achieved by using meaningful IoT paradigm and implementation. Accordingly, SDGs can be monitored for achieving sustainability goals.

There are many examples of IoT deployments around the globe which highlight sustainable community development. In the following some examples from the developing countries are presented [28].

- SDG 10, and 16: Secure biometric cash is being provided to refugees in Jordan by using the retina scan connected to financial IoT
- SDG 7,9, 11: Fire and smoke detection IoT with alarms is being used in highly dense urban settlements in Kenya and South Africa
- In Indian Ocean, the buoy IoT supports an early warning tsunami monitoring system
- In east Africa and India, the low income households are being powered by micro solar electricity off-grid IoT
- Black carbon sensing IoT supports cooking stoves monitoring in Sudan
- Public transportation connected mini buses IoT in Kenya is being used to monitor acceleration, speed, and braking to control risky driving
- SDG 12, 13, 14, 15: In East Timor, cloud based IoT supports motoring the illegal fishing activity
- Air pollution monitoring IoT to sense outdoor air pollution in Benin
- Acoustics based sensing IoT are being used to monitor see bird migration patterns and population count
- In Africa, animal tracking IoT supports game parks management
- In UAE, drone and ground camera monitoring IoT is being used by national park service
- In Indonesia, digital forestry IoT supports monitoring for illegal logging activity
- SDG 4: In South Africa, school attendance IoT has interconnected the students, faculty with the automated attendance system using biometric features
- SDG 1,2, and 8: In Kenya, a weather monitoring IoT supports accurate weather forecasting
- In India, pumps are interconnected using irrigation IoT for mobile-based irrigation management
- Agriculture IoT based on soil moisture sensing to tea crop in Sri Lanka and Rwanda
- Herd IoT in Namibia, Senegal, and Botswana, for animal tracking, keeping health records, and theft control.
- SDG 3 and 6: In Rwanda and Kenya, SMS and sensor-enabled water pumps to support villagers

- Cellular connected cool chain IoT is being used for refrigerated delivery of vaccines
- In west Africa, the medical IoT supports pulse, oxygen, and temperature, monitoring
- River monitoring IoT to sense river depth and rate of flow in Honduras

1.4.1 Examples from Advanced Countries

Examples of the sustainable IoT systems towards achieving SDG goals are discussed below:

- Internet of Things in Transportation and Logistics (IoTTL) [15]
- Agricultural IoT (Ag-IoT) [77]
- Internet of Battlefield Things [5]
- Wearable IoT [75]
- Internet of Body Things [20]
- Internet of Things in Smart Lighting and Heating [13]
- School Buses Transportation and Tracking IoT [26]
- IoT of autonomous vehicle and unmanned aerial systems [18]
- Payment facilitator [39]
- Micro-Transit IoT [10]
- Truck fleet IoT with charging stations [30]
- Multi-model transportation and logistics IoT [30]
- Garbage Monitoring IoT [29]
- Waste and Storm overflow monitoring IoT [53]
- Energy, Smart Meter, and Renewable Energy Systems IoT [45]
- Urban parking IoT [4]
- Mobility modeling and management IoT [63]
- Traffic Counting IoT [62]
- City utilities IoT [61]

1.5 IoT Challenges for Sustainability

Since IoT market is still in infancy, there is need of comprehensive business models and proof-of-concept implementation. By employing the sustainability goals during the design phase of the IoT is required to attain its full potential and economic benefit. Regulations, governmental incentives, monetary benefits, and tax credits, industry goodwill are some of the methods to encourage consideration of the sustainability goals at the system analysis and design of the IoT projects. An efficient business model is vital for sustainable IoT development. Introduction of accreditation programs to certify sustainability goals of the IoT is needed.

The management of huge amount of data being generated through connected ubiquitous IoT projects is a major challenge because of its competitive and analytical value. The collection, ownership and storage of data, its usage and sharing, sensitivity and privacy are some of the contentious issues that need to be solved.

The emergence of multitude of IoT platform providers has caused fragmentation which is hindering the critically desired consensus for standard development in the area of sensors, interfaces, and radios. The interoperability issues limit the choice of available hardware for IoT projects and inter-system integration also suffers because of the closed standards. Collaboration among different stake holders particularly the standardization efforts can help to reduce the impact of fragmentation. Opening up the data will also lead to development of cross-industry systems. These technical partnerships can also be used to integrate different technologies together to provide a unified front end.

The lack of large-scale IoT infrastructure due to low interest from investments from public and private sector is also hindering sustainability goals. The utilization of existing infrastructure, encouraging investors for IoT infrastructure through policy incentive, simplified legal and regulatory frameworks will help in development of IoT infrastructures at a scale. Joint symposium of government, academia, and industry leaders should be organized to discuss the sustainability promise of IoT in water, energy, urban environment, and transportation areas.

1.6 IoT Definitions

In this section, the IoT definitions as conceived by different standard bodies are presented.

1.6.1 Institute of Electrical and Electronics Engineers

> A network of items, each embedded with sensors which are connected to the Internet [1].

1.6.2 International Telecommunication Union

The International Telecommunication Union Telecommunication Standardization Sector (ITU-T) has defined IoT as a vision with technological and societal implications:

> Internet of things (IoT) is a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving inter-operable information and communication technologies [36].[1]

According to this recommendation, the IoT, by using sensing and communications capabilities, utilizes things to serve different types of application needs while ensuring security and privacy. The elements (terms) of the IoT paradigm are given below [36]:

- Device. A piece of equipment with the mandatory capabilities of communication and the optional capabilities of sensing, actuation, data capture, data storage, and data processing.
- Things. An object of the physical world (physical things) or the information world (virtual thing).

> An infrastructure of interconnected objects, people, systems, and information resources together with the intelligent services allow them to process information of the physical and the virtual world and react—[79].[2]

1.6.3 Internet Engineering Task Force

The Internet Engineering Task Force (IETF) excludes TCP/IP based Internet from the IoT domain because of private networks. To be considered an IoT it has to contain both IP and other protocols. IETF defines IoT as:

> The Internet of Things is the network of physical objects or "things": embedded with electronics, software, sensors, and connectivity to enable objects to exchange data with the manufacturer, operator, and/or other connected devices [34].[3]

[1] ITU-T Rec. Y.2060 (06/2012) Overview of the Internet of things.

[2] IT4IT References Architecture—ISO/IEC JTC1 WG10.

[3] IETF.

IETF definition of “things”:

> In the vision of IoT, “things” are very various such as computers, sensors, people, actuators, refrigerators, TVs, vehicles, mobile phones, clothes, food, medicines, books, etc. These things are classified as three scopes: people, machine (for example, sensor, actuator, etc.), and information (for example, clothes, food, medicine, books, etc.). These “things” should be identified at least by one unique way of identification for the capability of addressing and communicating with each other and verifying their identities. In here, if the “thing” is identified, we call it the “object.” [34]

1.6.4 National Institute of Standards and Technology

The National Institute of Standards and Technology (NIST) defines IoT as:

> Internet of Things (IoT)—involves connecting smart devices and systems in diverse sectors like transportation, energy, manufacturing and healthcare in fundamentally new ways. Smart Cities/Communities are increasingly adopting CPS/IoT technologies to enhance the efficiency and sustainability of their operation and improve the quality of life [48].[4]

Internet of Things Architecture (IoTIA) describes IoT in the following manner:

> It can be seen as an umbrella term for interconnected technologies, devices, objects, and services [8, 33].

1.7 Architecture of IoT Paradigm for Sustainability

The Internet of Things (IoT) for sustainability concept is based on the defining network of things and people in various environmental and natural settings goals to achieve sustainable goals. This pertains to application of IoT concepts to these

[4]NIST.

settings using sensing and communication technologies, systems and tools tailored to various applications domains and for different use cases. The sensing elements provide the interface to physical world which and are linked through communication technologies.

1.7.1 IoT Elements

The Internet of Things for sustainability consists following elements:

- Sustainability Things. It is integral part of the IoT paradigm with the ability to have physical or virtual connection to the IoT system.
- Sensors/Actuators. An instrument/equipment for environmental, climate, forestry, water, and energy sensing. It consists interface for networking and communications, and may have on-unit processing, data storage capabilities.
- Networking and Communications. To support interconnection of sustainability things and sensors/actuators components.
- Sustainability IoT System. It consists of interconnection of different elements such as things, sensors, and communication components integrated together to perform certain unique functions,
- Holistic Sustainability IoT Paradigm. It is the paradigm in which different IoT systems work together in order to achieve sustainability goals for a particular environment These environments are shown in Fig. 1.2.

1.7.2 IoT Functions

The proper functionality of these sustainability IoT components is vital to meet requirements and achieve sustainability goals. A clear description of these sustainability goals coupled with requirement is need for integration into the holistic sustainability IoT paradigm for various applications. A detailed list of these functions along with examples is given in the following.

- In IoT, the sensing function is used to sense physical, logical, and biological properties of different environments in the physical world in the analog and digital domains. Accordingly, this data becomes as input to subsequent functions of the IoT can be used by data collection, networking, data storage, processing, and decision making functions. Examples include cloud sensing, soil sensing, and water sensing. Different examples of sensing mechanisms in various sustainability IoT sensing phenomena are discussed in detail in this book in subsequent chapters.
- The data collection is a major function of the IoT in which data is gathered, combined, and processed for a particular environment that provides the ability to combine and process some data of interest within a given IoT system.

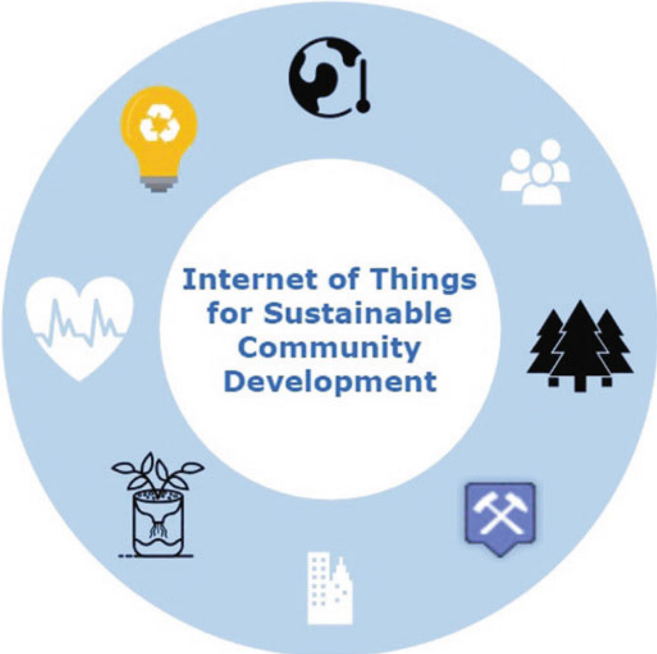

Fig. 1.2 The Internet of Things (IoT) for sustainable community development

- The networking function of the IoT is used to transport sensed data from different locations to storage location and cloud for subsequent decision making function. These could function in delay tolerant and delay sensitive fashion depending on the latency requirement of a particular sustainability paradigm. In the IoT for sustainability paradigm the networking tiers contain many layers including satellite, aerial, terrestrial, underwater, and underground networks. These network tier functions are discussed in the next section. The network interface cards are used to implement the networking and communications functions in the IoT paradigm and provide connective between links. The Ethernet adapter (IEEE 802 Standard), long-term evolution (LTE) Bluetooth, and ZigBee are some examples of these networking interface cards.
- The data storage and cloud function of the IoT are related to storing the data and information over the spatial and temporal variation. The examples of data storage functions include precipitation data, soil moisture data, hydrometer data, air temperature, wind speed and direction, water flow in different water bodies, nutrients and ion concentrations, and forest inventory.
- The processing function of the IoT converts raw sensed data to the useful information and provide it to decision making function, where it can be utilized by managers and policy makers. The center pivot control algorithms of actuator units in the sensor-guided irrigation management systems are one example of the

processing function where data is fed from underground sensors in the field of digital agriculture. Feedback control is another example.

- Decision making. In this IoT function, a decision is made based on the data collection and processing and accordingly, appropriate actions are taken which results into corresponding changes in the physical world to achieve the desired sustainability goal. Some of the examples these functions include flow control based on flow nutrients sensing, correct application of water treatment based on contaminants sensing, proper irrigation based on soil moisture sensing, cardiac treatment based on hear conditions, and fertilizer application based on the crop needs. It also includes functionality related to the human interaction with the IoT systems using graphical user interfaces, touch displays, and voice interfaces. The cybersecurity, encryption, and authentication are other functionalities.

1.8 Networking for Sustainability IoT Paradigm

The IoT for sustainable development will be deployed at large scales by using networking and advanced 5G/6G communication architectures to serve a wide variety of applications in different area. These communication networks are discussed below.

1.8.1 Five-Tier Network

The potential of current terrestrial networks is too less to support ubiquitous coverage connectivity requirement of sustainable IoT in climate, water, ocean, and energy areas. Therefore, to support these IoT paradigms, a multi-dimensional network with capability to integrate terrestrial and non-terrestrial systems is required. A five-tier network can support this integration and consists of five different tiers including space, ground, air, underwater, and underground. In Fig. 1.3, a design of multi-tier network is shown [83]. The sixth generation (6G) networks will have this capability to integrate multiple tiers which are explained below.

1.8.1.1 Terrestrial Network Tier

The terrestrial networks are the main tool to provide wireless connectivity for most of the sustainability IoT paradigms discussed in this book. Terrestrial networks will have the capability to operate in low frequencies, microwave spectrum, mm-wave, and THz bands. To support higher data rated (e.g., Tb/s), such as sustainable water and climate measurements, the THz band can be utilized. Energy-efficient mmWave communication devices based on a hybrid beamforming approach can also support real-time high-data rate communication needs. These networks will have high density deployments because of the higher attenuation in mm-wave and THz.

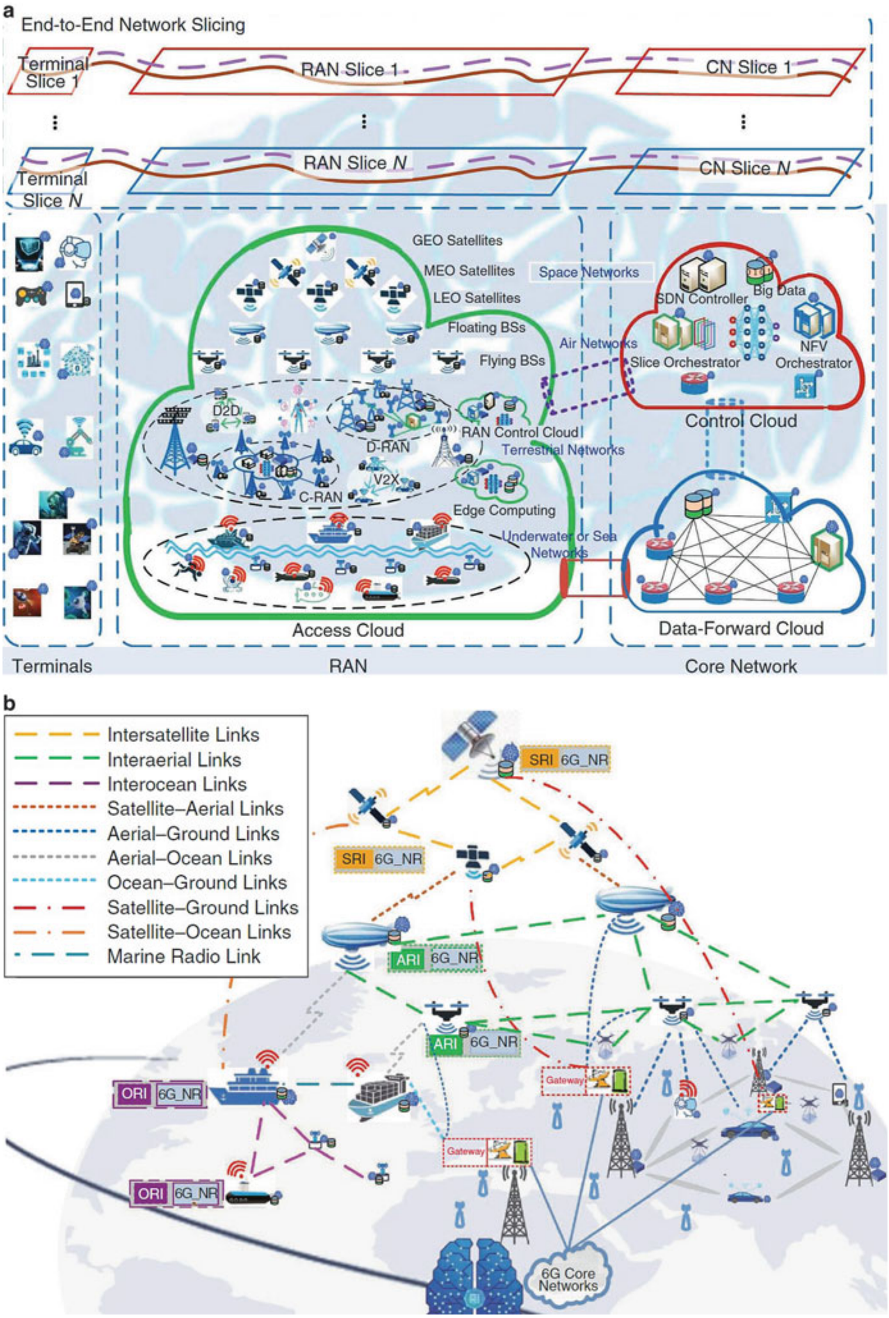

Fig. 1.3 The multi-tier network design [83]. The (**a**) network architecture and (**b**) interface design and operation of large-dimensional and autonomous networks. GEO: geostationary Earth orbit; LEO: low-Earth orbit; MEO: medium-Earth orbit; CN: core networks; D2D: device to device; C-RAN: cloud radio access networks; D-RAN: distributed radio access networks; ORI: ocean radio interface; SRI: satellite radio interface

Optical fiber is needed as backbone of these networks. The important technologies for the terrestrial networks are shown below [82]:

- The millimeter wave, Terahertz communications, full-duplex communication
- MIMO, distributed antenna arrays, DMIMO
- Interference cancellation, cognitive radio networks, NB-LPWAN
- Underwater/underground, large-scale network design, sensor networks
- Cellular networks, device-to-device, cyberphysical systems
- vehicular networks, UAV connectivity, safe UAV operation, green cellular networks
- Cyber threat defense, mobile computing, network estimation, content delivery networks
- Statistical signal processing, multimedia networking, security, and privacy
- Smart grid, cloud-fog platforms, software-defined networking, and mobile edge networking

Moreover, the conventional SDRs with novel mmWave radio can be used to create unique solutions by combine beam agility for highly directional communication in mobile environments with ultra-low-power characteristics. The design of novel low-loss hybrid electronically scanned arrays (ESA) capable of beamforming at millimeter wave (mmW) frequencies for next-generation high data-rate communications systems will be central for sustainable IoT realization.

1.8.1.2 Space-Based Wireless Network Tier

The wireless coverage requirements of the IoT for sustainability can be supported by space network by using satellites [6]. The future space network can utilize densely deployed low-medium-geostationary Earth orbit satellites to provide connectivity uncovered and undeserved area (e.g., IoT for sustainable digital agriculture). In agriculture, the irrigation and water management community has measured soil moisture to inform water management and irrigation decisions for decades. Automated technologies have largely replaced the use of hand-held/manual soil moisture technologies because of difficulties associated with taking manual soil moisture readings in production fields in remote locations.

In the last decade, wireless data harvesting technologies have developed that provide managers and users real-time access to soil moisture data, which, has resulted in more effective water management decision making. Unfortunately, advanced automated and wireless soil moisture measurement technologies still face practical application challenges. One challenge is a lack of consistent and robust wireless service in rural communities that prevent immediate access to soil moisture data. Another is the difficulty of installing soil moisture sensors early in the growing season and removing them at season end. Currently, users must drive long distances to install and remove sensors in different locations during the growing season, which creates problems in deploying advanced technologies in production fields.

Therefore, wireless underground soil moisture devices imbedded permanently in the soil, coupled with robust, reliable, and continuous wireless network services through satellites in rural agricultural communities, will significantly contribute to the adoption of technology and sustainable practices in production fields. For long-range, high data rate satellite to field communications in sustainable digital agriculture, the satellites with mm-wave communications can be deployed.

1.8.1.3 Aerial Network Tier

The recent advancements in technology have made possible to deploy air networks in low frequency bands, microwave spectrum, and mm-wave bands using aerial base stations mounted on unmanned aerial vehicles complemented by space networks. The aerial networks can enable IoT paradigms in the harsh areas where terrestrial networks are unable to provide coverage [12]. One application of aerial networks is in IoT for sustainable water where pollution level monitoring and advanced nutrient measurements are used in water bodies to assess water quality to assists regulators for pollution policy making.

Currently, the UAV potential in sustainability IoT is limited in part by their ability to navigate spaces precisely and in a cost-effective manner. The existing mechanisms to support localization are often hampered by cost (e.g., GPS-RTK), service gaps (cell towers), or crowded environments (e.g., GPS).

1.8.1.4 Underwater Network Tier

The underwater networks will enable sustainable IoT monitoring applications oceans, estuaries, rivers, lakes, streams, canals, and wetlands [7, 17, 64, 78]. Due to different wave propagation characteristics in the water medium from over-the-air (OTA), the acoustics and laser propagation can be utilized to attain higher data rates for in underwater communication and networking. It has applications in sustainable climate IoT in tsunami and undersea earthquake monitoring.

1.8.1.5 Underground Network Tier

In a new type of wireless communications (wireless underground (UG) communications) [2, 76], radios are buried underground and communication is conducted partly through the earth. The underground communication (UG) solutions are in their infancy and depend on off-the-shelf radios, which are not designed for the medium. For example, the maximum attainable communication ranges for underground-to-underground links are limited to a few meters, which prohibits the establishment of multi-hop underground networks. On the other hand, UG radios can establish communication with aboveground devices at distances over 200 m. While promising, these distances are still limited for some applications,

e.g., agricultural automation where large fields need monitoring with a limited network architecture to mobile data harvesting components [19]. In addition, the data rates attained by commercial off-the-shelf (COTS) solutions are limited to a tens of kbps, which prohibits data-hungry applications, including real-time control and navigation components.

To enhance wireless UG communication ranges, a novel theoretical framework for UG beamforming using adaptive antenna arrays to improve wireless underground communications performance [55] has been devised. A soil moisture adaptive beamforming (SMABF) algorithm was developed for planar array structures and simulations show, with different optimization approaches, range can be significantly improved. Similarly, multi-carrier underground communication through soil-adaptive sub-carrier and system bandwidth operation can significantly improve data rates [54, 57]. Currently, practical *and large-scale* evaluations of these techniques are cost prohibitive, limiting rapid commercialization for practical applications.

Underground networks support many unique applications in sustainability IoT by using wireless UG communications (e.g., stormwater and wastewater monitoring IoT and agricultural IoT). Existing over-the-air (OTA) wireless communication solutions face significant challenges in meeting the unique requirements of Ag-IoT applications. Therefore, these IoT paradigms for sustainability can use a diverse set of UG communication requirements and realistic scenarios to implement the communication range- and capacity-enhancing solutions in large scales. The integration of UG communications with Ag-IoT will help conserve water resources and improve crop yields [24, 27, 70, 74]; advances in Ag-IoT will benefit underground infrastructure and landslide monitoring, pipeline assessment, underground mining, and border patrol [3, 19, 54, 56–58, 76].

1.9 Wireless Communications for Sustainability IoT

In the following section, the key wireless communication technologies and drivers are discussed for the sustainability IoT.

1.9.1 Key Drivers for Next-Generation Wireless Systems in Sustainability IoT

- The operation frequency in the spectrum is moving from the radio bands to sub-terahertz (THz) bands and visible spectrum (e.g., visible light communications).
- The drive for automation and intelligence in wireless networks is relying on use of advanced technologies such as artificial intelligence (AI) and machine learning.

- More robust and dynamic networking architectures to meet goals of sustainable development.
- These innovations will also drive development in novel applications based on networking architectures.

1.9.2 Wireless Requirements for Sustainability IoT

The wireless communications and networking requirements for sustainability IoT requires innovation to increase data rates, capacity, connectivity, spectrum usage, energy efficiency, and mobility [23]. The key requirements are listed in the following:

- Peak Data Rates. The current peak data rates of 5G are around 10 gigabits per second (Gbps), whereas to meet sustainability IoT demands, the data rates of 1 Tb/s are required. This hundred times higher data rates demand than the current can be met by the next-generation technologies such as 6G, where the peak back-hual and front-haul data rates of 10 Tb/S can be achieved.
- Due to multitude of technologies operators vying for the scarce spectrum, spectrum efficient communications are vital for sustainability IoT. Particularity, in multi-tier networks, the same connectivity zones will be covered by multiple access network tiers, causing severe interference among tiers within in the paradigm. Therefore, advancement in interference mitigation, suppression, and cancellation techniques are required. Integration of licensed and unlicensed technologies (e.g., short-range Wi-Fi and long-range cellular) is also necessary to connect all sustainability things in different IoT applications.
- Application Specific Data Rates. For some scenarios, such hyper-spectral mineralogy sensing techniques, application specific data rates of 1–10 10 Gb/s rates are required.
- Extreme energy efficient technology and devices are required to support prolonged uninterrupted operation in some of the sustainability IoT scenarios such as urban underground infrastructure monitoring, storm and sewer overflow monitoring, and underground soil sensing. For example, IoT devices can awake from the sleep mode for data reception after periods of longer duration to extend battery life.
- Latency and Mobility. To archive quality of service (QOS), an OTA latency of 0.01–0.1 ms and extremely high mobility (621 miles/h) is required for sustainability IoT paradigm. More, low latency space-to-air and space-to-ground links are needed.
- Novel gateways, protocols, and standards are required to integrate different network tiers. One example of this link is interconnection between IoT devices in aerial networks and sensors in underground and underwater networks. Other examples include aerial to ground stations, space to aerial to ground. Things to people interaction gateways can utilize computer vision, always-on discovery and

awareness, and machine learning. Moreover, advancements in Things-to-Things (T2T) communication technologies are needed.
- Connectivity Density. For water climate monitoring IoT applications, a very high density of approximately 145 devices/mi^2 and with subnetwork capacity of more than 1 Gb per second per square mile. This will help to attain interoperability across multiple sustainability paradigms.
- Cybersecurity. It is discussed in detail in Chap. 10.

1.9.3 Wireless Standard Applications to Sustainability IoT

1.9.3.1 RF Wireless Modem Chipset

The chipset with ability to support multiple wireless and cellular standards will play cortical role to achieve the regional and local connectivity in different applications in sustainability IoT paradigm (e.g., health, security, and energy). In this regard, innovations are needed to produce cost-effective and scalable RF wireless modem chipset design [52]. Any such chipset will support multiple bands and modes with power saving, battery life for up to a decade through advanced power saving with Bluetooth, voice, and Wi-Fi interfaces with backward compatibility. Other important wireless interfaces include GSM, LTE FDD and TDD, EDGE/EGPRS, DC-HSPA, LR-WPAN, and TD-SCDMA. AllJoyn Open Connectivity Foundation (OCF) is an open source framework inter- interface/device/application secure communication protocol supports discovery of devices manufactured by different vendors.

1.9.4 Standardization for Sustainability IoT

1.9.4.1 Long-Term Evolution (LTE) IoT

The long-term evolution (LTE) is an enabler for high performance and scalable sustainability IoT services can provide high data rate (Gigabit) [46]. It has high energy and power efficiency to address sustainability IoT needs. It combines improved machine type communication (eMTC Cat-M1) and the narrowband IoT (NB-IoT) for narrowband applications (Cat-NB1) and supports grant-free uplink, and multi-hop mesh. The low complexity, long range, and low power communications in sustainability IoT can be supported by using NB-IoT and eMTC (e.g., agriculture, wearable, health, smart meters, and climate). The LTE Direct is a device-to-device (D2D) protocol that uses LTE user authentication, resource allocation and timing features to provide neighbor discover, and connectivity to mobile nodes in the node proximity.

1.9.4.2 802 Wi-Fi Standards

The Wi-Fi has the great potential to provide connectivity to many IoT devices and things to achieve sustainability. These 802.11 Wi-Fi standards which can be utilized for sustainability IoT are shown below [31]:

- 802.11ah for low power operation in the 902–928 MHz frequency bands
- 802.11ac for 5 GHz spectrum unlicensed uses
- 802.11ad for WiGig networking
- 802.11ay for 60 GHz unlicensed uses
- 802.11ax for dense networking environment

Many important alliances include: HomePlug Alliance [49], Bluetooth Special Interest Group (Bluetooth SIG) [11], Open Connectivity Foundation (OCF) [43], the Thread Group [40], the Powerline technologies, and oneM2M. In a recent trail of high data rate communications, it has been shown that it is possible to achieve 100 Gb/s in microwave spectrum using multiple-input, multiple-output (MIMO) for a communication range of approximately 1 mile. This trial has shown the feasibility of better communications in microwave as compared to the millimeter (mm-wave) communications [81]. The important trial parameters are: 8×8 LOS MIMO, 2.5 GHz channel bandwidth in the 70 and 80 GHz (E band) with high spectrum efficiency of 55.19 b/s/Hz. Recently, an autonomous unmanned broadband smart surface vessel was operated remotely using 4G network for water quality and pollutants sensing.

1.9.4.3 5G and 6G Wireless Communications

Currently, the 5G communications [22] are envisioned as big technology driver for the Internet of Things particular for sustainable community development (e.g., smart cities, public safety, transportation, smart energy usage, connected and autonomous vehicles, and health care). Through its better than 4G speeds, energy and spectrum efficiency, low latency and higher reliability, the 5G wireless networking the vital to realize sustainability IoT and its real-time data-intensive communication needs in applications such real-time video streaming for police body cams and medical imaging.

Currently, there are many challenges in 5G. Although in 5G, the ultra-reliable, low latency communications (URLLC) [69] has the potential to support sustainability IoT applications, its performance suffers from the small packet size issues that is a limiting factor for higher data rates. More, the support for sensing, communications, things, and system convergence is limited in 5G and more improvements are needed in this area. Another needed feature in regard to IoT the support for visualization the radio access network (vRAN) due to front-haul challenges. Moreover, in 5G dynamic pricing models are needed based on capacity and usage. The limitations of slow data rates, convergence of IoT sensing, systems,

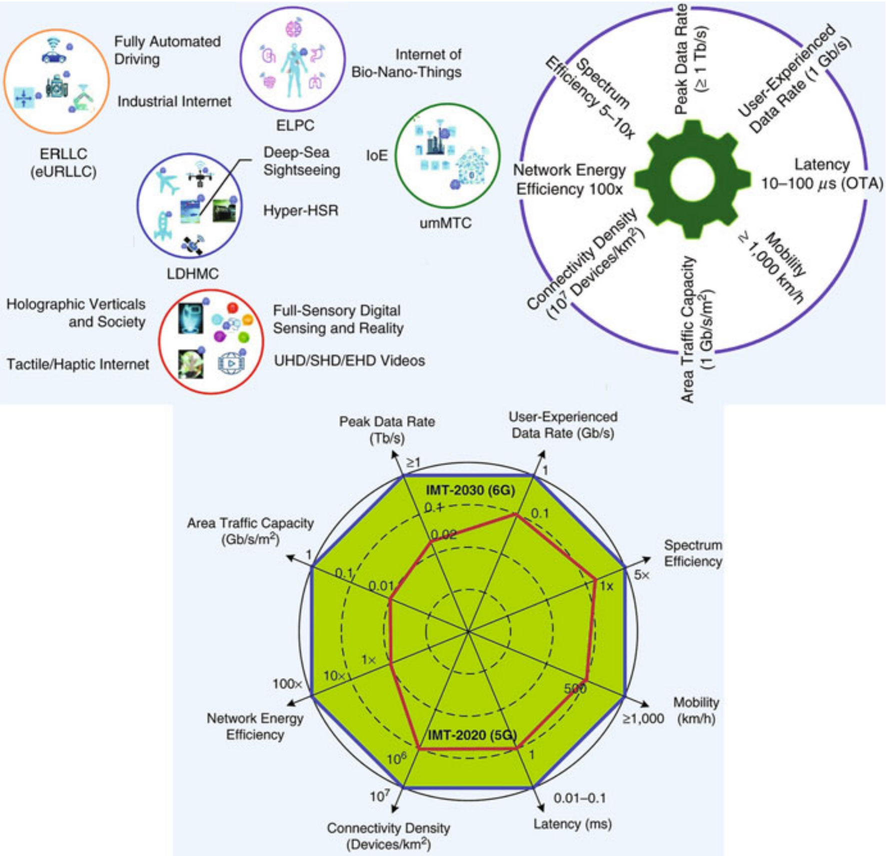

Fig. 1.4 The 6G application scenarios [83]. (**a**) The 6G application scenarios, (**b**) typical scenarios and (**c**) key capabilities of 6G networks

and wireless communication, and open interfacing related issues can be solved with novel networking architectures of 6G wireless communications which is discussed next (Fig. 1.4).

The road-map to 6G wireless communications has already started to take shape. The requirements and trends are being defined with 6G enabling technologies for connected intelligence and things. The prominent 6G goals and desirable features are listed below [83].

- Support of extremely high data rates (in Tb/S) as compared to current 4G wireless communications
- High energy efficiency, energy harvesting, and wireless power transfer to support IoT
- The ultra-low latency in data and control planes in few microseconds

- Support for a very wide spectrum in GHz and THz bands such as from 72 GHz to 141 GHz and 1000 GHz to 3000 GHz,
- Convergence of space and ground based wireless networks to provide global connectivity and coverage
- Intelligence built into the network through machine learning, enhanced mobile broadband (eMBB) [44] ultra-reliable, low latency communications (URLLC) [69], and massive machine-type communications (mMTC) [50].

1.9.5 Artificial Intelligence and Wireless

The artificial intelligence (AI) will play a key role in optimization and autonomous functionality of the network [80]. A list of AI algorithms in networking is shown in Fig. 1.5. The AI enabling technologies in wireless communications are discussed below:

- Application of AI training methods specifically the machine learning in wireless communications will bring innovation and performance improvements. This can be achieved intelligence management and autonomous agent.
- The neural networks based deep learning for data driven approaches in wireless.
- AI applications to address network management, complexity, and QoS issues in next-generation wireless networks.

1.9.6 Wireless Spectrum Paucity

The wireless spectrum scarcity is major challenge for heterogeneous wireless systems. The demand for wireless spectrum to meet the needs of sustainability IoT applications is increasing which could be met the identification and allocation of additional spectrum. Spectrum sharing through cognitive radios is another approach to address the issue of dearth of spectrum where unlicensed users can use the spectrum when the primary user is not present in the licensed spectrum. The efforts of the United States Federal Communications Commission (FCC) to address this issue through rulemaking are presented below [21, 73]:

- Use of Spectrum Bands Above 24 GHz For Mobile Radio Services
- Establishing a More Flexible Framework to Facilitate Satellite Operations in the 27.5–28.35 GHz and 37.5–40 GHz Bands
- Petition for Rulemaking of the Fixed Wireless Communications Coalition to Create Service Rules for the 42–43.5 GHz Band
- Petition for Rulemaking of the Fixed Wireless Communications Coalition to Create Service Rules for the 42–43.5 GHz Band

Network Functions		AI Algorithms	Descriptions
Network Architecture			
SDN	Decoupling the control and data-forward function to achieve programmable network management and configuration.	. DNN . Enhanced Q-Learning . Support Vector Machines . Decision Trees . Self-Organizing Maps . Biological Danger Theory . Gradient-Boosted Regression . Deep Reinforcement Learning	. Achieving dynamic network orchestration and slice management according to real-time network information and service requirements . Providing on-demand dynamic network configuration and critical network management. . Achieving autonomous network management and maintenance to improve network performance and reduce operational expenditures. . Achieving optimal multilevel computing resource allocation according to resource state, network load, and computing task profile to improve computing efficiency
NFV/ NS	NFV: Decoupling software and hardware and eliminating the dependency of network functions or dedicated hardware NS: Creating multiple instances of parallel network functions to achieve on-demand network deployments.		
Cloud/ Fog /Edge Computing	Cloud Computing: Providing for stocking and accessing data and applications and using networks of shared IT architecture containing large pool of systems and servers. Fog Computing: Extending computing to the edge of the network and facilitating the operation of computing, storage and networking services between end devices and cloud computing data centers. Edge Computing: Bringing processing close to the data source and improving the speed and performance of data transport as well as devices and applications on the edge.		
PHY Air-Interface Protocol Layers			
Physical Layer	. Providing reliable data transmission, including channel coding, modulation, MIMO precoding, OFDM Modulation, and so on. . Providing channel estimation	. DNN . K-Means . CNNs . CCNNs . Autoencoder	. Innovating end-to-end PHY design and reducing the complexity of the MIMO-OFDM receiver. . Improving PHY performance, especially for such scenarios as high mobility.
Data Link Layer	. Performing frame flow-related operations, including scheduling (or resource allocation), power control, error control, error correction, flow control, synchronization, data packet queuing, and so on.	. DNNs . Q-Learning . Reinforcement Learning . Supervised Learning . Transfer Learning	. Achieving optimal user scheduling by channel estimation and traffic prediction based on trained models to improve network performance and increase radio-resource efficiency. . Optimizing retransmission redundancy version and reducing transmission overhead.
Network Layer	. Responding for RRC connection management, mobility management, BS association, BS clustering, load management, and routing management.	. DNNs . Q-Learning . Reinforcement Learning . Supervised Learning . Un-supervised Learning . K-Means . Transfer Learning	. Optimizing service cells and data offloading cells by traffic prediction. . Optimizing multiple connectivities . Achieving mobility prediction and hand-over process optimization to improve mobility performance. . Providing optimal path for data transmission by learning routing strategies and extracting useful information from raw network data directly. . Achieving optimal BS lustering and controlling the size of a cluster in a dynamic

Fig. 1.5 AI algorithms in networking [83]

- Allocation and Designation of Spectrum for Fixed-Satellite Services in the 37.5–38.5 GHz, 40.5–41.5 GHz, and 48.2–50.2 GHz Frequency Bands
- Allocation of Spectrum to Upgrade Fixed and Mobile Allocations in the 40.5–42.5 GHz Frequency Band
- Allocation of Spectrum in the 46.9–47.0 GHz Frequency Band for Wireless Services
- Allocation of Spectrum in the 37.0–38.0 GHz and 40.0–40.5 GHz for Government Operations

1.9.7 Rural Broadband Telecommunications

The broadband infrastructure is vital for the proper functionality of sustainability IoT. In rural areas, there are many challenges being faced by the service providers (e.g., network extension to under covered areas, need of infrastructure upgrades to meet increasing demand) [51]. Rural broadband is important to provide connectivity to agricultural users and things.

1.9.8 Satellite Communications

The satellite communications also play an important role to provide connectivity to the sustainability IoT paradigm things. A Global Low Power Wide Area Network (LPWAN) to support IoT devices around the world by combining the Inmarsat's global connectivity as backhaul connectivity and Actility's LoRaWAN technology. Various applications are enabled by this network such cattle tracking systems for remote ranches, water and soil moisture monitoring in agriculture, and remote oil facility monitoring in areas where cellular coverage does not exist. Other sustainability IoT applications that can benefit from satellite communications include smart grid, underground and surface pipeline monitoring, vehicular fleet tracking, water resource management, disaster response, remote and critical infrastructure monitoring, environmental protection, wind turbine monitoring, and border security.

1.10 Organization of the Book

The book covers the research and innovation ecosystem of the sustainable Internet of Things in the following major areas:

- Climate change
- Sustainable energy systems
- Sustainable water
- Human health
- Sustainable mining
- Decision agriculture
- Storm and wastewater
- Sustainable forestry

While each of these areas will emphasize a core IoT research challenges and solutions while leveraging their shared traits, interdependencies, and expertise to converge on applications of IoT to sustainability challenges. In the following, we highlight the above mentioned areas each with a collection of supporting concepts that are developed and explored in this book. Many of these areas emphasize cross cutting activities that support major cohesive goal of sustainability.

Chapter 2: Internet of Things for Environmental Sustainability and Climate Change Our world is vulnerable to climate change risks such as glacier retreat, rising temperatures, more variable and intense weather events (e.g., floods, droughts, frosts), deteriorating mountain ecosystems, soil degradation, and increasing water scarcity. However, there are big gaps in our understanding of changes in regional climate and how these changes will impact human and natural systems, making it difficult to anticipate, plan, and adapt to the coming changes. The IoT paradigm in this area can enhance our understanding of regional climate by using technology solutions, while providing the dynamic climate elements based on IoT sensing and communications that is necessary to support climate change impacts assessments in each of the related areas (e.g., environmental quality and monitoring, sustainable energy, agricultural systems, cultural preservation, and sustainable mining). In the IoT in Environmental Sustainability and Climate Change chapter, a framework for informed creation, interpretation and use of climate change projections and for continued innovations in climate and environmental science driven by key societal and economic stakeholders is presented.

Chapter 3: Internet of Things in Agricultural Innovation and Security The agricultural Internet of Things (Ag-IoT) paradigm has tremendous potential in transparent integration of underground soil sensing, farm machinery, and sensor-guided irrigation systems with the complex social network of growers, agronomists, crop consultants, and advisors. The aim of the IoT in agricultural innovation and security chapter is to present agricultural IoT research and paradigm to promote sustainable production of safe, healthy, and profitable crop and animal agricultural products. The chapter covers the IoT platform to test optimized management strategies, engage farmer and industry groups, and investigate new and traditional technology drivers that will enhance resilience of the farmers to the socio-environmental changes. A review of state-of-the-art communication architectures, and underlying sensing technology and communication mechanisms has been presented with coverage of recent advances in the theory and applications of wireless underground communication. Major challenges in Ag-IoT design and implementation are also discussed.

Chapter 4: Internet of Things for Water Sustainability The water is a finite resource. The issue of sustainable withdrawal of freshwater is a vital concern being faced by the community. There is a strong connection between the energy and water which is referred as energy-water nexus. The agriculture industry and municipalities are struggling to meet the demand of water supply. This situation is particularly exacerbated in the developing countries. The projected increase in world population requires more fresh water resources. New technologies are being developed to reduce water usage in the field of agriculture (e.g., sensor guided autonomous irrigation management systems). Agricultural water withdrawal is also impacting ground and surface water resources. Although the importance of reduction in water usage cannot be overemphasized, major efforts for sustainable

water are directed towards the novel technology development for cleaning and recycling. Moreover, currently, energy technologies require abundant water for energy production. Therefore, energy sustainability is inextricably linked to water sustainability. The water sustainability IoT has a strong potential to solve many challenges in energy-water nexus. In this chapter, the architecture of IoT for water sustainability is presented. An in-depth coverage of sensing and communication technologies and water systems is also provided.

Chapter 5: Internet of Things for Sustainable Forestry Forests and grasslands play an important role in water and air purification, prevention of the soil erosion, and in provision of habitat to wildlife. Internet of Things has a tremendous potential to play a vital role in the forest ecosystem management and stability. The conservation of species and habitats, timber production, prevention of forest soil degradation forest fire prediction, mitigation, and control can be attained through forest management using Internet of Things. Use and adoption of IoT in forest ecosystem management are challenging due to many factors. Vast geographical areas and limited resources in terms of budget and equipment are some of the limiting factors. In digital forestry, IoT deployment offers effective operations, control, and forecasts for soil erosion, fires, and undesirable depositions. In this chapter, IoT sensing and communication applications are presented for digital forestry systems. Different IoT systems for digital forest monitoring applications are discussed.

Chapter 6: Internet of Things in Sustainable Energy Systems Our planet has abundant renewable and conventional energy resources but technological, capability and capacity gaps coupled with water-energy needs limit the benefits of these resources to citizens. Through IoT technology solutions and state-of-the-art IoT sensing and communications approaches, the sustainable energy-related research and innovation can bring a revolution in this area. Moreover, by the leveraging current infrastructure, including renewable energy technologies, microgrids and power to gas (P2G) hydrogen systems, the Internet of Things in sustainable energy systems can improve challenges in energy security to the community with a minimal trade off to environment and culture. In this chapter, the IoT in sustainable energy systems approaches, methodologies, scenarios, and tools is presented with detailed discussion of different sensing and communications techniques. This IoT approach in energy systems is envisioned to enhance the bidirectional interchange of network services in grid by using Internet of Things in grid that will result in enhanced system resilience, reliable data flow, and connectivity optimization. Moreover, the sustainable energy IoT research challenges and innovation opportunities are also discussed to address the complex energy needs of our community and promote a strong energy sector economy.

Chapter 7: Internet of Things for Sustainable Human Health The sustainable health IoT has the strong potential to bring tremendous improvements in human health and well-being through sensing, monitoring, of health impacts across the whole spectrum of climate change. The sustainable health IoT enables development of a systems approach in the area of human health and ecosystem. It allows

integration of broader health sub-areas in a bigger archetype for improving sustainability in health in the realm of social, economic, and environmental sectors. This integration provides a powerful health IoT framework to sustainable health and community goals in the wake of changing climate. In this chapter, a detailed description of climate related health impacts on human health is provided. The sensing, communications, and monitoring technologies are discussed. The impact of key environmental and human health factors on the development of new IoT technologies is analyzed.

Chapter 8: Internet of Things for Sustainable Mining The sustainable mining Internet of Things deals with the applications of IoT technology to the coupled needs of sustainable recovery of metals and a healthy environment for a thriving planet. In this chapter, the IoT architecture and technology is presented to support development of a digital mining platform emphasizing the exploration of rock-fluid-environment interactions to develop extraction methods with maximum economic benefit, while maintaining and preserving both water quantity and quality, soil, and, ultimately, human health. New perspectives are provided for IoT applications in developing new mineral resources, improved management of tailings, monitoring and mitigating contamination from mining, and tools to assess the environmental and social impacts of mining including the demands on dwindling freshwater resources. The cutting-edge technologies that could be leveraged to develop state-of-the-art sustainable mining IoT paradigm are also discussed.

Chapter 9: Internet of Things in Water Management and Treatment The goal of the water security IoT chapter is to present a comprehensive and integrated IoT based approach to environmental quality and monitoring by generating new knowledge and innovative approaches that focus on sustainable resource management. Mainly, this chapter focuses on IoT applications in sewer and storm water management, and the human and environmental consequences of water contaminants and their treatment. The IoT applications using sensors for sewer and storm water monitoring across networked landscapes and water quality assessment, treatment, and sustainable management are presented. The studies of rate limitations in biophysical and geochemical processes that support the ecosystem services supporting water quality are presented and the application of IoT solutions based on these discoveries is discussed.

Chapter 10: Internet of Things for Sustainability: Perspectives in Privacy, Cybersecurity, and Future Trends In the sustainability IoT, the cybersecurity risks to things, sensors, and monitoring systems are distinct from the conventional networking systems in many aspects. The interaction of sustainability IoT with the physical world phenomena (e.g., weather, climate, water, and oceans) is mostly not found in the modern information technology systems. Accordingly, the actuation, the ability of these devices to make changes in real world based on sensing and monitoring, requires special consideration in terms of privacy and security. Moreover, the energy efficiency, safety, power, performance requirements of these device distinguish them from conventional computers systems. In this chapter, the cybersecurity approaches towards sustainability IoT are discussed in detail. The

sustainability IoT risk categorization, risk mitigation goals, and implementation aspects are analyzed. The openness paradox and data dichotomy between privacy and sharing is analyzed. Accordingly, the IoT technology and security standard developments activities are highlighted. The perspectives on opportunities and challenges in IoT for sustainability are given. Finally, the chapter is concluded with sustainability IoT cybersecurity case studies.

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Chapter 2
Internet of Things for Environmental Sustainability and Climate Change

Abstract Our world is vulnerable to climate change risks such as glacier retreat, rising temperatures, more variable and intense weather events (e.g., floods, droughts, and frosts), deteriorating mountain ecosystems, soil degradation, and increasing water scarcity. However, there are big gaps in our understanding of changes in regional climate and how these changes will impact human and natural systems, making it difficult to anticipate, plan, and adapt to the coming changes. The IoT paradigm in this area can enhance our understanding of regional climate by using technology solutions, while providing the dynamic climate elements based on integrated environmental sensing and communications that is necessary to support climate change impacts assessments in each of the related areas (e.g., environmental quality and monitoring, sustainable energy, agricultural systems, cultural preservation, and sustainable mining). In the IoT in Environmental Sustainability and Climate Change chapter, a framework for informed creation, interpretation and use of climate change projections and for continued innovations in climate and environmental science driven by key societal and economic stakeholders is presented. In addition, the IoT cyberinfrastructure to support the development of continued innovations in climate and environmental science is discussed.

2.1 Introduction

The global climate is changing rapidly mainly because of the human activities over the period of last five decades [80, 137]. This change is project to continue in the foreseeable future depending on the heat-trapping gas emissions in the environment and sensitivity of the climate of the Earth on these emissions [108]. From 1895 to 2020, an increase of 1.3–1.9 °F in average temperature has been observed in the USA with substantial increase after the year 1970 [7, 25, 110]. The change in global annual mean surface-air temperatures (ocean and land combined) is shown in Fig. 2.1. An increase of 8 in. has been observed in global sea levels since 1880 with a projected increase of up to 4 ft by the end of this century. The ice covered areas (surface extent) in sea, land, and lakes are decreasing with increase in temperature [63, 116]. The warmest month records are being

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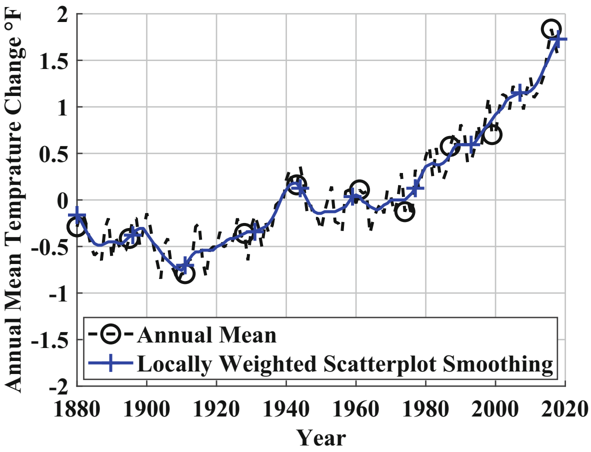

Fig. 2.1 The change in global annual mean surface-air temperatures (ocean and land combined) based on NASA/GISS/GISTEMP data

broken consistently and human caused global warming combined with natural changes in climate is making too difficult to accurately predict climate variations [8, 79, 117, 119, 124]. Accordingly, due to the interdependence of the growing season on the frost-free period, the length of growing season has been increased and will continue to increase [4, 30, 38, 62, 68, 74, 142, 157, 158, 173]. Moreover, the average precipitation has increased with corresponding increase in intensity of the extreme downpours and precipitation [7, 94, 128, 139, 151]. Furthermore, more variations are being observed in extreme weather occurrence patterns (e.g., the frequency of the cold waves have decreased but its intensity has increased) [9, 32, 44, 55, 83, 120, 146]. Similarly, the same patterns are being observed for droughts and flooding, where droughts intensity has increased [49, 82, 121]. Since 1980, the hurricanes have become more frequent and intense spanning over longer duration which is also related to the heavy downpours and intense storms [20, 43, 106]. The frequency and intensity of the winter storms, damaging winds, thunderstorm, and tornadoes are also the subject of climate change investigation [17, 65, 112, 155]. The ocean acidification (the decrease in the pH levels of the oceans) is increasing due to the one-fourth absorption of the atmospheric carbon dioxide emission in oceans which is impacting marine echo system [33]. The change in annual mean surface-air temperatures in USA is shown in Fig. 2.2.

The IoT is being envisioned as an effective tool to combat the climate change [81]. Through its sensing and monitoring capabilities, it provides insights into root cause of climate change by sensing the amount of CO_2 and different greenhouse gases in our atmosphere [150]. The emissions of greenhouse gases from burning of fossil fuels can be sensed in real time. Accordingly, the carbon sequestration processes and rates can be monitored to increase the storage of carbon captured in forests which helps to offset emissions. Furthermore, the novel atmospheric "things" and technology can be developed to permanently reduce the atmospheric CO_2 with integration into the climate IoT.

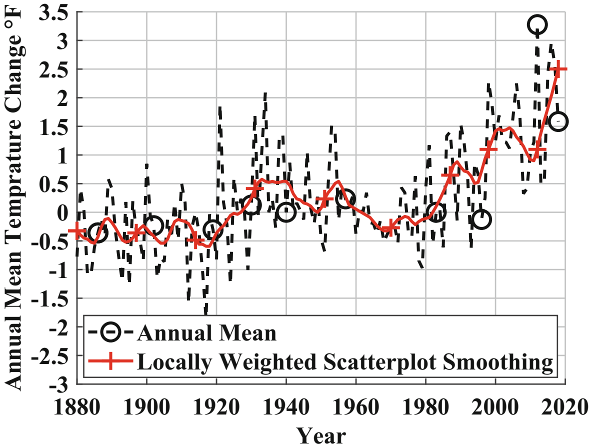

Fig. 2.2 The change in annual mean surface-air temperatures in USA based on NASA/GISS/GISTEMP data

The climate IoT is also useful in climate change anticipation and adaption preparation. Its sensing and communication technologies coupled with prediction systems and models clear uncertainty and provide useful insights into the exact nature of the climate changes. The IoT enabled climate decision making tools can predict predicting how the climate will change and how the ecosystem is likely to respond to the climate change and other factors affecting it. The IoT technology has enabled empirical investigations on impacts of elevated greenhouse gases [126]. It also supports simulations of ecosystem's response in different climatic conditions (both current and future). With this new knowledge the environmental and atmospheric management practices are tailored and accordingly novel management techniques can be developed. By utilizing the contemporary scientific and technological advancements, the climate IoT has the potential to meet immediate and long-term goals and applications needs. This architecture provides better understanding and insights into the global ecosystems and supports informed decision making. This enhanced understanding of the Earth system from universal to regional scales has the potential to enhance our ability to assess water resources, predict weather patterns, forecasts climate, and increased understanding of ecosystem health. The impact of these factors on our community determines the need of development of applications utilitarian to the society.

2.2 Climate Change IoT Things for Environmental Sustainability

The worldwide environment consists of the atmosphere, ecosystems, air quality, hydrosphere, lithosphere, atmosphere chemistry, chromosphere, biosphere, land and ocean bio-geochemical processes [77]. The following climate change elements

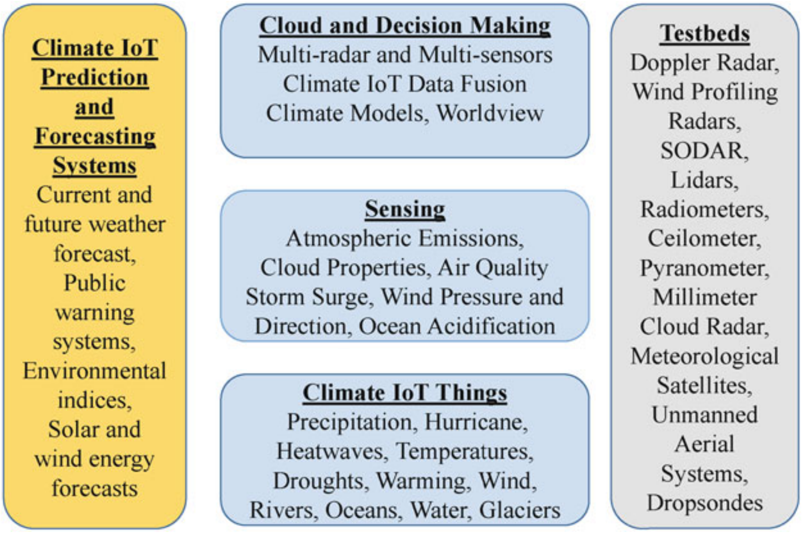

Fig. 2.3 The architecture of environmental sustainability and climate change IoT

outline main contextual components related to functionalities of the IoT in environmental sustainability and climate change (Fig. 2.3):

- Severe precipitation, hurricane, and heatwaves events
- Storm surge, shoreside and in-land flooding, and increase in sea levels
- Ocean acidification and alteration of marine ecosystems
- Decline in water availability and elevated water competition aggravated by increase in population and land-use practices
- Surging carbon dioxide levels
- Rising temperatures, droughts, and warming caused by wildfires
- Enhanced demand of water for energy and water
- Variation in timing of streamflow caused by snow melt
- Shrinking glaciers and permafrost thawing
- Water scarcity and reducing supplies of fresh water

2.3 Climate IoT as the Sustainability Enabler Framework

2.3.1 Holistic System

The integration of sensors, communication technologies, reporting, prediction, and forecasting and surface meteorological systems in the environmental sustainability and climate change IoT paradigm has many potential benefits [159]. Novel

visualization and decision-support tools for changes in ocean temperature, coastal inundation, and sea-level at decision-relevant scale can be developed for real-time analysis using multi-radar and multi-sensors IoT elements. These systems will serve as indicators of climate impacts on ocean and coastal resources and other sectors which will aid in enhanced weather forecasting using adaptive atmospheric sensing and sampling and radar technology with resolution of 10,000 m for deterministic forecast and 20,000 m for ensemble forecast.

2.3.2 Novel Sensing Methods

The data from new sensors and robotic floats for biogeochemical, biooptical, and pH measurements can be fused in the cloud for real-time analysis [104]. The multi-dimensional atmospheric analysis prototypes can be integrated into the system with data assimilated from wide area meteorological zones for providing robust warnings using real-time radar sampling techniques. The environmental sustainability and climate change IoT paradigm can help prototyping the weather and fire behavior modeling system for local firefighting applications. The climate IoT paradigm brings improvements in accurate understanding and better planning by enabling climate forecasts at multi-time-scales, projections of future climate trends and change for support policy decisions. It enables integration of following sensing and monitoring systems.

2.3.3 Solar Radiation and Soil Moisture Data

In environmental sustainability and climate change IoT paradigm, the solar radiation and soil moisture data can be linked for improved insights into the wind, water content, and temperature profiles [37]. The aerial sensing systems composed of different types of sensors (e.g., LiDAR, Doppler radar, spectrometer, dropsondes [131], and radiometer) also provide diverse insights [91, 156]. These observations are useful to fill gaps in measurements of different parameters of water cycle including water vapor transport, precipitation, snow, river flow, sea-ice, waves, water level, and surface energy budget terms including evapotranspiration and aerosols. Moreover, the impact of natural changes such as solar and volcanic activities, varying aerosols and greenhouse gases radiative forcing can be observed at large scale.

- Tropical and extra tropical oceans and cyclones, ocean basin, and sea levels
- Storm surges, droughts, heat waves, and wildfires
- Land-based ice sheets and hydrologic cycle
- Simulations of ocean, atmosphere, and land-surface processes
- Surface albedo, water vapor, clouds, and geomagnetic conditions

- Temperature, precipitation, extreme events, and pollution
- Air quality modeling, wildfires, and dust storms

2.3.4 Forecasting Models

For understanding and predicting the impacts of climate variabilities, extreme and precipitate climate changes, there is a strong need of full range of tools for environmental prediction and projection forecasts on different spatial and temporal scales [11, 123]. The climate IoT paradigm is also useful to ascertain the effects of the slowly changing Arctic Oscillation (AO) weather patterns through simulations [8]. New insights can be gained about the impact of ocean-atmosphere link on weather forecast through interconnection if these currently disjoint systems [40]. Similarly, it enables hurricane inner nest for global forecasting system. The advantages of multi-model, stochastic-, and multi-physics ensemble generation can be realized with novel methods of uncertainty condition representation [2]. Moreover, with the data obtained from the sensing and monitoring systems, the advanced statistical models can be developed for reliability improvement (e.g., tropical storm and extra-tropical storm inundation model) [59, 111, 118, 143]. It also enables development of new disciplines such as storm behavior climatologies by providing access to data collected over span of multiple decades. Furthermore, prototypes of high resolution climate models and prediction systems can be developed including novel downscaling methods for climate systems across different temporal/spatial scales [12, 42, 48, 49, 51, 138]. The data assimilation process in ionosphere and thermo-sphere in forecast models can provide better insights. A global climate grid scale model is shown in Fig. 2.4. Other important models are listed below:

- Route inundation storm surge
- Storm scale
- Geospace model in local geomagnetic storm
- Radiation environment at aviation and orbital altitudes
- Assimilative models
- Ionosphere plasmasphere
- Wind energy
- Coupled human and natural systems

2.3.5 Emissions Monitoring

The black carbon, methane, and nitrous oxide emissions can be quantified through climate IoT sensing techniques with high certainty [10, 45, 58, 75, 90, 92, 93, 101, 149, 154, 167, 170]. Accordingly it impact on the environment and clouds can be

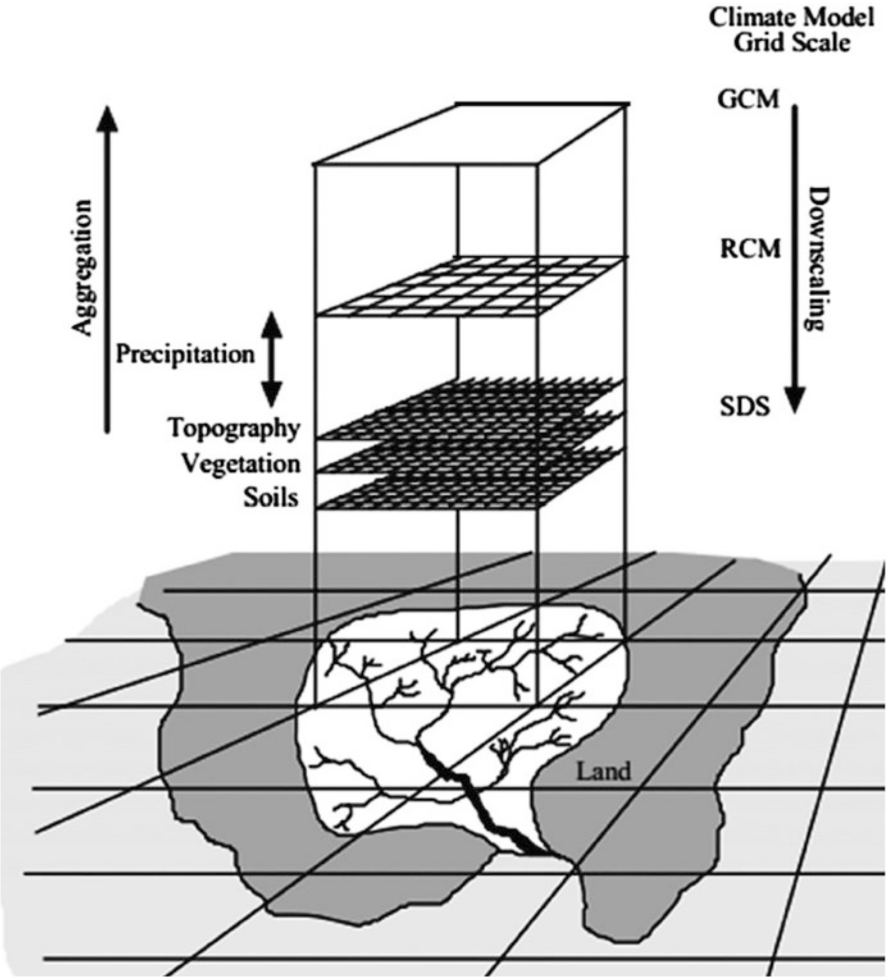

Fig. 2.4 The global climate grid scale model [136]

assessed by developing reliable flux estimates. The impact of four replacement compounds on extremely high ozone layer, surface air quality, and climate can be evaluated for solvents, refrigerants, and other blow agents [13, 16]. It also enables air chemistry assessment of effects of urban, gas, and oil development emissions on urban air quality [144]. Moreover accurate models can be developed to quantify climate sink and forcing for the following:

- Atmospheric aerosols
- Greenhouse gases
- Aerosol interactions
- Stratospheric chemistry

2.4 Climate Communication Technologies and Systems

With the advancement in systems development, many novel atmospheric monitoring and mapping, and communications technologies have been developed. These are discussed in the following section.

2.4.1 Doppler Radar

Data about the velocity remote objects can be obtained using a special type of radar that measures the Doppler effects [23, 95]. A microwave EM signal is transmitted from the radar towards the desired target that is in motion [22, 41]. The frequency of returned signal (bounced from the object) is analyzed to get accurate measurement of target speed.

The Doppler effect can be produced using four different methods:

- Coherent pulsed (CP)
- Pulse-Doppler
- Continuous wave (CW)
- Frequency modulation (FM)

The narrow-band filters are employed in Doppler radars to cancel interference from low speed and immobile objects (e.g., birds, clouds, insects, and wind) (Fig. 2.5).

2.4.2 Wind Profiling Radars

Wind profiling radar (also called wind profiler) [61, 98] is a type of Doppler radar that functions in the VHF frequency band from 30 to 300 MHz and UHF frequency band 300–1000 MHz frequency bands. It operates by directing the beam energy to the normal offset by few degrees. The wind profiling radar differs from the scanning Doppler in their processing and production of Doppler [97]. In the profiler, hundreds of low intensity pulses are transmitted to create Doppler velocity spectrum with a 30 s of dwell time. Whereas, in Doppler scanning radar resolved volume moments are produced by a limited number of pulses are transmitted with dwell time of few milliseconds.

2.4.2.1 Types of Wind Profiling Radars

Different types of wind profiling radars are explained below [147]:

- 404 MHz NOAA profiler network (NPN) Profiler is used for the deepest atmospheric coverage. It uses coaxial-collinear phased array antenna with antenna

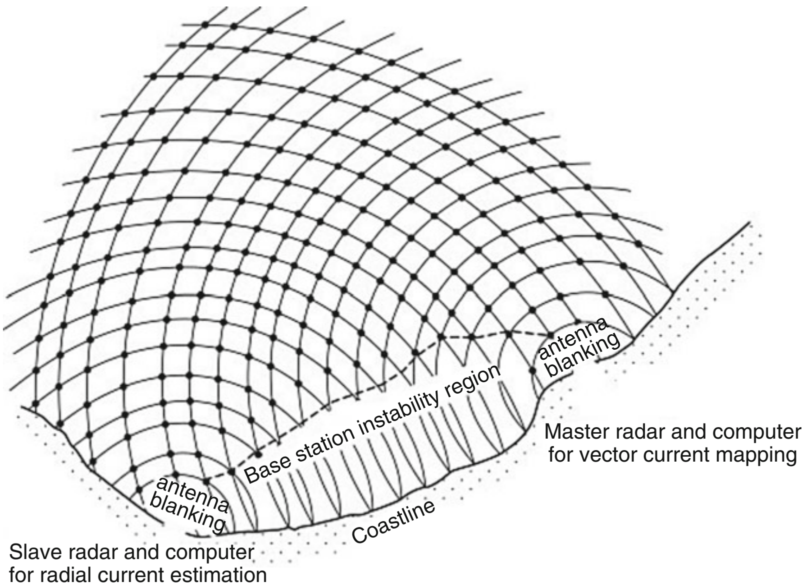

Fig. 2.5 Conceptual rendition of the spatial coverage of dual-site HF/VHF Doppler radar systems using two wide-beam transmit antennas. The dots represent the locations on the sea surface from which radial water-current vectors are derived using echoes received at both the radars [78]

diameter of 13 m and beamwidth of 4°. It can cover a height of up to 16,000 m with vertical resolution of 900 m. With peak transmit power of 6000 W, it can attain temporal resolution of 60 min. Due to its sophisticated hardware, it is considered expensive to fabricate and operate.

- 915-MHz boundary layer profiler is easy to build and operate yet it has limited height measurement capability beyond the boundary layer. It uses flat rectangular microstrip patch antenna with antenna diameter of 2 m and beamwidth of 10°. It can cover a height of up to 4000 m only with vertical resolution of 106 m. With peak transmit power of 500 W, it can attain temporal resolution of 60 min.
- 915-MHz quarter scale profilers are also easy to build and its height measurement capability is better than the boundary layer profiler. It uses coaxial-collinear phased array antenna with antenna diameter of 6 m and beamwidth of 10°. It can cover a height of up to 8000 m only with vertical resolution of 212 m. With peak transmit power of 2000 W, it can attain temporal resolution of 60 min.

The wind profiling radars can operate in two different modes: the Doppler beam swinging (DBS) and radio-acoustic sounding system (RASS) modes. Both modes are not supported simultaneously.

- In Doppler beam swinging (DBS) the beam is steered in three to five different radial directions for Doppler spectra measurements. Accordingly, the motion

of the horizontal winds radial component is measured for each direction to determine the horizontal wind profile. The longer time duration high mode pulse and shorter duration low mode pulses are employed for low and high height resolution, respectively.
- In Radio-acoustic sounding system (RASS) mode acoustics wave and radio waves are employed simultaneously to determine. The velocity of sound wave is analyzed as function of height to determine vertical air motion and temperature.

2.4.2.2 Sonic Detection and Ranging (SODAR)

The sonic detection and ranging (SODAR) is a type of wind profiling radar that is used for meteorological purposes [26, 97, 99]. The sound waves are impacted by turbulence when propagating in the atmosphere. SODAR measures that scattering process to determine the above-ground wind speed at different heights. It is also used to analyze the thermodynamic structure of the low atmospheric region. It is based on the Doppler effect mechanism of the frequency change of sound waves relative to the moving target. It operates in the 4.5 KHz sound wave spectrum. Three different acoustic beams are transmitted. A vertical beam which goes straight upwards and two beams are emitted at 17° normal to the Earth. The reflected signal is received and fast Fourier transform (FFT) operation is performed for frequency domain analysis. Accordingly, the Doppler-shifted frequency is used to determine the wind speed. It works for the height range of up to 200 m.

In bi-static SODARs the sender and receiver can be located at a distance (usually up to 10 m) instead of being housed in the same unit. In conventional setting, SODARs are only able to get measurements from a fixed height. With electronically scanned array of acoustics microphones, the receiver can get multiple views from different heights with accurate measurements of velocity variations in turbulence.

2.4.2.3 Wind Profiling LiDARs

LiDAR (light detection and ranging) is used to illuminate the target by using laser light and sensing the reflectance by using light sensors [114, 123]. A 3-D results can be produced by using the delay in laser arrival time and wavelengths. A wind profiling also works on the Doppler effects principal where the back-scattering of light particles from the atmosphere is used to measure the wind turbulence and speed at different heights. The performance can be further improved by using laser beam steering mechanism where interference form the undesired components can be reduced or totally eliminated to produce high quality results.

2.4.3 Microwave Radiometers

At larger wavelengths in the spectrum, the microwave measurements of the electromagnetic (EM) radiation are used for wavelengths between 1 mm and 1 m [15]. Microwave measurements are classified into the longwave and shortwave measurements. These are explained in the following:

2.4.3.1 Longwave Measurements

The longwave measurements are done using wavelengths that are longer than approximately 4.0 μm. These are further classified into three types:

Longwave Broadband The longwave broadband measurements are used for direct radiant energy diffusing in vertical upward and downward direction within the broadband and infrared wavelengths [51].

Longwave Spectral The longwave spectral measurements are employed for radiant energy resolving in spectrum at infrared wavelengths.

Longwave Narrowband It includes radiant energy measurements in the narrowband infrared wavelengths.

2.4.3.2 Shortwave Measurements

The shortwave measurements are done using wavelengths that are less than 4.0 μm. These are further classified into three types:

Shortwave Broadband The shortwave broadband microwave is used to measure the intensity of the radiant flux in the visible spectrum and infrared-approaching spectrum chunks of the shortwave broad-wavelength bands.

Shortwave Narrowband The shortwave narrowband is employed to measure the intensity of the radiant flux in the visible and infrared-approaching spectrum chunks in shortwave narrow-wavelength bands.

Shortwave Spectral The shortwave spectral measurements of radiant energy flux intensity are done at spectrum resolving visible and infrared-approaching wavelengths.

Radiometers are receivers of the frail EM energy which is transmitted from the surface of the earth, whereas the radars transmit their own EM pulses to the surface [15, 96]. The radiometric measurements are done using different methods such as active radar, active LiDAR, passive broadband radiometers, and passive sensors [127]. The measurements are important source atmospheric data which is obtained by measuring the decay of the energy of the electromagnetic waves when traveling through the atmosphere.

2.4.4 Ceilometer

A ceilometer is an aerosol concentration measurement device that operates on the light sources such by using laser to obtain the cloud heights and base [27]. It is considered as a type of the LiDAR with much less range. There are two different types of the ceilometers.

2.4.4.1 Optical-Drum Ceilometer

An optical-drum ceilometer consists of a detector, recorder, and moving projector and works on the triangulation technique to get the height of the cloud based light spot projection.

2.4.4.2 Laser Ceilometer

A laser ceilometer carries both the laser transmitter and receiver in the same unit and has the capability to transmit very short pulses of few nanoseconds duration to the atmosphere. These work on the same principles as the LiDAR and can be used to map atmospheric volcanic ashes and clouds.

2.4.5 Microbarographs

The microbarograph, also named as barograph, is used to measure pressure of the atmosphere in millibars with reference to sea levels. A graph paper, wrapped around the moving cylindrical bar, is used for recording the continuous pressure [64].

2.4.6 Pyranometer

A pyranometer is a device to determine flux density of solar radiation in hemisphere. It measures solar irradiance by surfaces of planar shapes [107]. Pyranometer is a special type of actinometer with wavelength range of 0.285 to 2.8 μm. It is used for measuring solar irradiance on a planar surface and it is designed to measure the solar radiation flux density from the hemisphere above within a wavelength range of 300–3000 nm. The sun emits solar radiation, which can be harvested for heat and electric energy uses. Many environmental indexes are produced from the data acquired from the pyranometer such as temperature, humidity, sun, and wind (THSW) and ET. Aerosol characteristics (e.g., scattering, phase, refraction index) can be produced through photometer sky radiance measurements inversion. Sun

photometer instrument is used to measure radiance at four frequencies in various scanning scenarios. The aerosol optical depth (AOD) is also measured using this instrument.

2.4.7 Millimeter Cloud Radar

The millimeter cloud radar (MMCR) works on the measurement of vertical speed of the particles also called the Doppler velocity [3, 28]. When clouds are above the radar, the MMCR measures its vertical profile by using the reflectivity which is a measure of the intensity of the returning signal. Accordingly, the size of the cloud particle is determined by using colors. A rising particle is indicated by a warm color and fall particles are specified by cool colors. Similarly, the width of spectrum shows the diversity of the cloud particles (the typical particle size is approximately 0.2 μm.)

2.4.8 Sonic Anemometers

An anemometer is an instrument commonly found on meteorological stations. It is used for rapid 3-dimensional wind speed measurements with higher accuracy. It is also used for turbulence measurements [66]. It supports sub-meter (0.01 m/s resolution) in 6000 cm range with rates of 0.1 KHz which is helpful for detailed turbulence analysis. Sonic anemometers operate by measuring the time taken for a pulse of sound to travel between a pair of acoustic radios (both radios are equipped with transmission and reception facility, which is alternated for bi-directional measurements). Since, the velocity of the sound wave is affected by many factors (e.g., fog, dust, temperature, and pressure), accurate measurement requires sensitive anemometer equipment. Moreover, the heavy downpour also affects the measurements and leads to variations in pulse travel time. Similar type of errors is also observed in icy conditions requiring anti-ice warming equipment to be integrated with the equipment. To reduce the effects of the distortions caused by the air flow, calibrations are performed in wind tunnels to correct direction related errors. The wind angle and direction can be measured by employing more than two radios. It supports operation in 0.02, 0.05, and 0.1 kHz frequency bands.

2.4.9 Environmental and Meteorological Satellites for Remote Sensing

Meteorological satellite plays a vital role in climate change and variability analysis. These are used to obtain the meteorological, oceanographic, and terrestrial data

of the Earth [6, 18, 19, 35, 36, 130, 160]. The meteorological and environmental satellites are used for different types of EM waves measurements that are either emitted or reflected form the Earth such ocean and land surface and from the atmosphere [18, 39, 67, 71]. These satellites have the capability to measure the wide range of EM spectrum including the visible light spectrum, radiations in microwave and infrared bands [61, 76]. These are explained in the following sections.

2.4.9.1 Geostationary Satellites

The geostationary satellites functions in orbits and these spin in the direction of Earth rotation [164]. Therefore, with reference to the surface of the Earth, a static position is maintained over the Earth at very high altitude (23,922 miles). Due to this factor, these satellites have the capability to observe the same region of the Earth and are frequently used in weather applications such as cloud properties sensing. However, in comparison to the low altitude satellites, high resolution analysis cannot be supported. These satellites provide consistent data flow to ground stations about the planet after every half hour. Two main instruments on the GOES satellite are an imaging and sounding system. The imaging instrument supports are capable of taking measurements at four different frequencies in visible, water vapor infrared and thermal infrared spectrum for cloud water, and surface temperature monitoring. The Geostationary Operational Environmental Satellite (GOES) East and West are the two examples of the geostationary satellites:

- The Geostationary Operational Environmental Satellite East is also known as GOES-12. It is located 75° west longitude over the equator at 7. It is used to cover the American continent.
- The Geostationary Operational Environmental Satellite West satellite, positioned over 135° west longitude, this is also called GOES-10. The eastern pacific region is covered by these satellites. Similar satellites are also being operated to cover the provide coverage at global scale
- The Geosynchronous Meteorological Satellite (GMS) is also known as GMS-5. It is used to cover the western pacific region. It is located over the equator at 140° east longitude. With the exception equipment of sounding hardware, all equipment found on the GOES-West and GOES-East satellites are also present on the GMS with same imaging capabilities.

2.4.9.2 Polar-Orbiting Satellites

The polar orbiting satellites generally are in comparatively low altitudes circular orbits in comparison to the geostationary satellites. The typical height is approximately 435–500 miles and it takes 1.6 h to complete the orbit. Moreover, as compared to geostationary satellites, their position is not fixed rather these

continuously change their position with relative to the surface of the Earth. These can provide high resolution imaging but complete coverage of the Earth takes many days by using multiple satellites.

Examples of the polar-orbiting satellites are given below:

- The Defense Meteorological Satellite Program (DMSP). These are used to provide meteorological coverage on diurnal basis about the oceanographic, meteorological, and terrestrial properties of the planet. DMSP satellites orbit at an altitude of approximately 830 km, collecting images across a 3000-km swath under both daytime and nighttime conditions. Each satellite views any point on the Earth twice a day and completes an orbit in about 101 min. Complete global coverage is provided every 6 h. The measurement instrument on DMSP satellites includes the Special Sensor Microwave Imager (SSM/I) [47, 69, 133, 163] for geophysical parameters, the SSM/T, and the SSM/T2 (atmospheric sounding instruments for microwave temperatures at different heights). These are used to gather data at four different frequencies using two polarization settings. The geophysical data provided by SSM/I consists of wind speed and temperature at ocean surface, land and water precipitation, and atmospheric water vapor.
- The NOAA Polar-orbiting Operational Environmental Satellites (POES) provide daily coverage
- Landsat satellites. Supports higher resolution and multi-spectral imaging
- French SPOT satellites. No daily coverage capability

2.4.9.3 More Meteorological Satellites

More weather imaging and atmospheric monitoring satellites are also used globally such as European Community operates Meteosat, China operates the Feng-Yun, Russia operates GOMS, and INSAT satellite is operated by India. Features of these satellites are explained in the following:

- Meteosat is a type of geostationary satellite. It is operated by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). Meteosat is used to obtain data using visible light, thermal infrared, and water vapor infrared wavelengths.
- Feng-Yun is operated by also a geostationary meteorological satellite. It is located at 105° east longitude. It is equipped with visible wavelength sensor system that senses radiation in one visible frequency and two infrared frequencies. This equipment has the capability of producing visible imaging of the Earth on a particular day.
- GOMS has the infrared equipment and is also Elektro and GOMS-1. It works on the geosynchronous weather imaging technology.
- The Indian INSAT satellite is located above the equator at approximately 90° east longitude. It is used to obtain images of Central Asia and Indian Ocean.

2.4.10 GPS Signals for Remote Sensing

A remote sensing tool has been proposed which uses signals from GPS satellite systems for sensing applications where GPS reflectivity data is utilized for weather forecast [14, 172]. GPS consists of 28 satellites which orbit approximately at an altitude of 12427 miles. Two different methods are discussed below:

2.4.10.1 GPS Limb Sounding for Atmospheric Reflectivity

In GPS, the position of the receiver is determined by the signal travel time from the satellite to receiver [87]. GPS signal reaches at the receiver through multiple paths which are reflected from the surrounding objects and surfaces. These multipath signals can cause destructive or constructive interference depending on the location of the object. However, this reflection is being utilized to obtain useful information about the sea ice, ocean state, soil moisture, snow pack, and sea ice. The GPS transmitted EM signal wave length is approximately 0.2 m. The reflections from these environmental parameters are investigated and novel GPS limb sounding techniques have been developed which are also called the occultation method. This technique produces accurate profiles of reflectivity in atmosphere.

2.4.10.2 GPS for Precipitable Water

GPS signals are also used to monitor the amount of precipitable water which is the entire water vapor in the atmosphere between two points in a column [14]. Due to complex permittivity of the water vapor, it absorbs and delays the EM waves traveling through the atmosphere. This can be measured by using interferometric instrument and is mapped to water vapor content. Another device sun photometer is also used to measure precipitable water by measuring the collimated solar radiation and the columnar aerosol optical depth (AOD).

2.5 Climate IoT Monitoring Systems

2.5.1 Cloud Properties Monitoring

The sensing of the vertical and horizontal distribution of macroscopic properties of clouds is done using active and passive remote sensing equipment [46, 145, 161]. The ceilometer is used to produce the vertical backscatter profile for cloud base height measurements. The Cloud, Aerosol Polarization and Backscatter LiDAR (CAPABL) is another type of cloud properties measurement tool. The microphysical cloud properties (e.g., shapes, sizes, water, and ice phases of the cloud particles) are also determined.

Microphysical Properties of Clouds The cloud properties sensing also involves microphysical measurements of thorough physical dimensions of the hydrometeor (an atmospheric phenomena related to clouds that involves water, water vapor, rain and other time varying characteristics of the clouds) [27, 29, 56, 88]. These measured hydrometeor characteristics are related to its phase, water and ice content, size, optics, and radar recurring properties.

Macrophysical Properties of Clouds The macrophysical properties of clouds involve measurements of cloud level parameters of clouds, that includes their place and position, dimensions, location, type, and the path of water and ice [28, 84, 85].

The cloud profiling instrument (profiler) operates in three different wavelengths. These include 915 MHz ultra-high frequency band, 2.835 GHz microwave band, and 50 MHz very high frequency. The radar sends energy and receives the back-scattered waves. Two types of turbulence phenomena are observed in these bands: Bragg scattering from reflectivity and Rayleigh scattering from hard objects. In these spectrum bands, the moisture and temperature are the primary sources of Bragg scattering, whereas the organic objects and hydrometers are the main cause of Rayleigh scattering. These instruments are used to observe atmospheric hydrometers.

2.5.2 Atmospheric Emissions Monitoring

The emission's scenarios [108] including different radiatively actives substances such as greenhouse gases and aerosols are monitored using LiDARs and other equipment which measures optical and scattering properties, size distribution, and aerosols extinction. This includes atmospheric monitoring for vertical and horizontal moisture, thermal, and kinetic properties and concentration of CO_2 and O_3 gases (e.g., radiatively active traces) using air-borne and surface based instruments.

2.5.3 Monitoring of the Surface of the Earth

The monitoring of the surface of the Earth involves measurements taken on, alongside, and underneath (less than two meters in the subsurface) the earth's earth-air interface. These observations ascertain characteristics such as soil's temperature and soil's volumetric water content, reflectivity of earth surface, momentum flux, latent and sensible heat, moisture, and CO_2 [34, 72, 100]. The numerical weather prediction models use these observations of earth surface, above ground and underground temperature, soil moisture, temperature of the radiative Earth skin, and surface reflectivity to provide current and foretasted values of these phenomena.

Surface Meteorology The land-based observations close to the Earth-air interface including precipitation, air temperature and pressure, moist content, and wind speed and direction are done using surface meteorology [70, 73].

Upper Air State Another important element of earth monitoring is the upper air state. The measurement techniques include balloon-borne, areal, and satellite-based observations. Many important parameters of the atmospheric profiles include geo-potential height, wind, moisture, temperature, and air pressure to support weather prediction models by providing input of these vital parameters.

2.5.4 Sea State Monitoring

The accurate information about the sea state is vital for weather forecasting and marine traffic [17]. The knowledge of sea state along with heat and moisture fluxes at multiple provide useful information at multiple scales. The sea state monitoring is the one using radars and drones. Other important sea state monitoring parameters include status of Arctic changes such as sea ice melting process, decline in sea-ice extent and thickness, wind and ocean circulation in North Atlantic. These are discussed in the next section.

2.5.4.1 OceanSITES

The OceanSITES is a network of global measurement stations for ocean to sea-floor and air-sea interaction monitoring [140]. It measures the surface and water column automated using sensors. The observations made using OceanSITES includes water transport, ocean acidification, meteorology, bio-geo-chemistry, carbon cycle, physical oceanography, and geophysics.

2.5.4.2 Air-Sea Heat Fluxes

In Atlantic observing system, the transport mooring arrays (TMAs) are employed in Atlantic Ocean to acquire long-term data of heat, volume, and freshwater fluxes of significantly strong flows. The air-sea heat-flux calculation is important for wave dynamics, kinematic and thermodynamic sensitivity analysis [171].

2.5.5 Arctic Measurements

The increasing temperatures have caused the rapid warming of the Arctic at a large scale due to which its sea cover has reduced. It has also induced the variation in heat

reflection and absorption from the ocean. The sunlight scattering, transmission, and absorption mechanisms of ice, snow, and water are different. Arctic measurements will play a vital role to get insights into the changing global weather patterns [24, 31, 53, 57, 85, 86, 115, 125, 148, 152, 156, 161, 169].

2.5.6 Hurricane Monitoring

To predict hurricane path and its intensity [103], reliable weather models are necessary. However, many physical model components that play a critical hurricanes are not understood very well and more measurements needed. In this regard, the identification and parameterization of heat fluxes and momentum over sea-air interface are required. The extension of similar analysis to the spray-filled transition layer is also needed for better accurate path prediction. The climate IoT with it capabilities of atmospheric observations and empirical measurement sin lab settings, coupled with models these parameterizations of sea-air momentum, and the heat flux can be better understood hurricane conditions. Different hurricane models are:

- The Global Forecast System (GFS)
- United Kingdom Meteorology (UKMET)
- Hurricane Weather Forecast Model (HWRF)
- Geophysical Fluid Dynamics Laboratory (GFDL)
- The European Medium Range Forecast Model (ECMWF)
- Navy Operational Global Prediction System (NOGAPS)

2.5.7 Solar Radiation Monitoring

Solar Radiation Network (SolRad-Net) is a network of sensors to provide high frequency solar flux measurements [135]. The Aerosol Robotic Network (AERONET) is network of distributed dynamic sun photometers to enable different ocean related applications [50]. The aerosol optical depth is done using the maritime aerosol network (MAN) element of AERONET. These measurements can be used to validate satellite, ground, and other aerosol based measurements.

A list of field testbeds with functionality and sensing capabilities for climate IoT integration is shown in Table 2.1.

2.6 Climate Databases Integration to IoT and Cloud

Climate IoT is envisioned as paradigm to manage and leverage the data from sensors and monitoring systems. Through cloud integration, it can handle complex data sets of high volume to support decision support systems designed to address complex

Table 2.1 A list of field testbeds with functionality and sensing capabilities for climate IoT integration

Testbed	Description
Arctic clouds in summer experiment	Observation of ice and sea conditions, clouds, atmospheric composition, and energy budget of earth surface
Boulder atmospheric observatory	Boundary layer analysis and long-term climate baseline measurements using is a 300 m meteorological tower for instruments
California nexus	Air quality and climate change airborne measurements using aircraft and surface measurements using mobile platform as well as fixed ground stations
CalWater	Analysis of atmospheric rivers and aerosols in clouds and precipitation using areal, ground, and sea-based measurements
Colorado airborne multi-phase study	Clouds and precipitation investigations
Coordinated observations of the lower arctic atmosphere	Low atmosphere thermodynamics analysis
Denver-Julesburg basin air quality study	Analysis of hydro-carbon emissions from gas and oil to observe methane
Dynamics of the Madden–Julian oscillation	Flux, sonde, and W-band radar measurements for MJO analysis
Front range air pollution and photochemistry testbed	Wind profilers/RASS and surface meteorology sensors for photochemistry, oxidant and aerosol formation and fate, flow and recirculation patterns
Discover air quality testbed	Air quality and pollution measurements
High wind gas exchange	Air-sea flux and wave observations
NOAA hydrometeorology testbed	High-impact regional precipitation, weather and land surface conditions analysis
Hurricane and severe storm sentinel	Hurricane formation and intensity change analysis in the Atlantic ocean basin
Intl arctic systems for observing the atmosphere	Arctic atmospheric observations of air-sea-ice flux, boundary layer dynamics, and clouds
Integrated characterization of energy, clouds, atmospheric state, and precipitation at summit	The clouds and precipitation analysis over the Greenland ice sheet using radar, LiDAR, precipitation, and radiosonde
Midlatitude continental convective clouds testbed	Cloud and precipitation analysis using radars
RV Mirai Arctic	Surface fluxes measurements using sonic anemometers and radiometers
Sea state	Wave and energy fluxes analysis during ice expansion at boundary layer

(continued)

Table 2.1 (continued)

Testbed	Description
Sensing hazards with operational unmanned technology	High impact weather prediction using unmanned observations
Storm peak cloud properties validation	Mixed-phase clouds and precipitation analysis using aircraft
Swedish–Russian–U.S. Arctic testbed	Cloud and boundary-layer observations with remote sensing equipment
Tropical ocean tropospheric exchange	Air-sea flux measurements of carbon monoxide
Uinta basin winter ozone	Tower-based measurements of surface fluxes, and ground-based measurements of surface, net irradiance, and meteorological variables
Wind forecast improvement testbed	Wind forecasting and wind energy modeling and applications
Hawaii ocean timeseries testbed	The climate observations using flux reference buoy sites
Winter storms and Pacific atmospheric rivers	Dropsonde system operations and data analysis to observe winter storms and Pacific atmospheric rivers
Experimental PBL instrumentation assessment	Remote sensing instrumentation for wind energy
Advanced vertical atmospheric profiling system	Global hawk dropsonde unmanned aircraft for atmospheric observations

environmental problems. Climate IoT also provides the opportunity design novel tools for searching, sharing, analysis, and visualization of data. A list of such data sets is given in Table 2.2.

2.7 IoT Enabled Indices

The climate IoT enables integration of following vital indices:

2.7.1 Air Quality Index (AQI)

AQI is an air quality pollution index [102]. The AQI index is determined for various air pollutants including sulfur dioxide, particle pollution, ground level ozone, and carbon monoxide. For each of these pollutants, the AirNow is used to report current and future pollution forecasts.

Table 2.2 Climate databases

Name	Data set description	Technology used in collection
International surface pressure data bank	The world's largest collection of pressure observations from 1856 to 2012. The ISPDv3 is a blend of many national and international collections of station, marine, and tropical cyclone best track pressure observations	Miscellaneous
Arctic summer cloud ocean cloud database	Cloud macro and microphysical measurements	Ka-band cloud radar, multichannel radiometer, and ceilometer
Arctic summer cloud ocean wind profiler database	Wind profiles and backscatter	449 MHz wind profiler radar
Daily hydro-meteorological data set for Mexico, the conterminous U.S., and southern Canada: 1950–2013	Hydrologic states, precipitation, maximum and minimum daily temperature and fluxes	A 6 km gridded product station
Hydrologic rainfall analysis XMRG data set	Four years of the California Nevada River Forecast Center (CNRFC) precipitation and temperature data sets with the XMRG	Miscellaneous
Air-sea flux	Ship-based flux observations	Satellite observations
Global ensemble forecast system reforecast data set	A 150 TB data set of global ensemble forecasts and a wide range of experimental forecast guidance based on these, including week-2 temperature and precipitation forecasts, week +1 precipitation forecasts, weeks +1 to +2 tornado forecasts	Miscellaneous
Worldview	More than 800 global, full-resolution satellite imagery layers for ash plumes, air quality, dust, drought, fires, severe storms, floods, smoke, water and ice, settlements, vegetation, and temperature	Satellite
Web soil survey (WSS)	Source of comprehensive soil related information	In-situ soil moisture measurements
Wave exposure model (WEMo)	Wind wave energy and the movement of seafloor sediment in enclosed water bodies such as lakes, coastal bays, and estuaries	Miscellaneous
Multiscale integrated models of ecosystem services (MIMES)	Georeferenced data sets as well as knowledge of ecological, economic, and social processes	Miscellaneous

2.7.2 *Drought Index (EDDI)*

The Evaporative Demand Drought Index (EDDI) [109] is drought monitoring and early warning tool. It provides early warning of developing drought and status of current droughts. The Standardized Precipitation Index (SPI) is another drought index used to monitor meteorological droughts.

2.7.3 *Environmental Sensitivity Index (ESI)*

The information about the coastal resources and other hazards such as oil spill, and sensitive shorelines can be obtained from ESI [52]. The ESI maps are utilized for hazard planning, to set safety priorities and practices.

2.7.4 *Coastal Drought Index Using Salinity Data*

Based on salinity data, a coastal salinity index (CSI) has been developed which provides monthly precipitation along with monthly mean salinity data to ascertain the probability of salinity for a specific month [129].

2.7.5 *Wildfire Threat Index (SAWTI)*

SAWTI is an index to forecast the fire potential by considering the wind potential. Surface temperature and relative humidity are the vital parameters for these fire-prone wind events monitoring [134].

2.8 Environmental Sensing Systems

In this section, different atmospheric sensing systems are discussed. A detailed list of these systems is given in Table 2.3.

2.8.1 *Precipitation Occurrence Sensor System*

The precipitation occurrence sensor system (POSS) is a type of Doppler radar that operates in X-band for precipitation sensing. It can sense type, intensity, and

Table 2.3 Environmental monitoring systems

Tool	Description
Twentieth century reanalysis	Global reconstruction of weather every 6 h from the surface of the earth to the tropopause back to 1851
Automated frost/heat forecast system	Frost and heat occurrences prediction in Vineyards
Atmos. river water vapor flux tool	Combines observations of wind profiles and integrated water vapor (IWV) to measure the IWV flux in the controlling layer and compares to operational numerical weather prediction prior and future forecasts
Atmospheric river detection tool	Automated objective software package to aid in the identification and characterization of atmospheric rivers to assist forecasters
Fairall–Banner sea-spray flux algorithm	A set of computer codes that allow estimation of air-sea momentum, heat, and moisture fluxes at hurricane wind speeds. Accounts for the effects of sea spray
Forecast reference evapotranspiration (FRET)	Bias-correction of FRET
Hydrologic model performance assessment tool	Set of R codes for calculating the performance metrics of hydrologic modeling. The developed metrics include Nash–Sutcliffe efficiency, runoff volume difference, modified correlation coefficient, percent bias, and time to peak. These functions can also automatically detect the miss of the USGS streamflow data to ensure the model assessment being executed on the apple-to- apple basis
Integrated characterization of energy, clouds, atmospheric state, and precipitation	Web page hosting near-real time measurements and data products from a suite of ground-based remote and in situ sensors characterizing the atmosphere, clouds, and precipitation at summit station on top of the Greenland ice sheet
MRMS NetCDF-XMRG format transformation tool	A set of Python codes which can transform the 1-km resolution multi-radar multi-sensor (MRMS) QPEs between the NetCDF and XMRG format. The tool also possesses the capabilities to perform the geo-reference and aggregation functions.
NOAA COARE bulk flux algorithm	A set of computer codes that allow estimation of air-sea or air-ice fluxes using bulk meteorological inputs. Meteorological and numerous trace gas fluxes are available
Snow-level product	A patented method to detect the level of the atmosphere where snow changes into rain

(continued)

Table 2.3 (continued)

Tool	Description
Vertical profile tool	Website allows users to extract different atmospheric products showing the vertical profile of the atmosphere. The products include single or multiple profiles on a date, a vertical transect between 2 points, a skew-T plot and a time by height plot. Data is extracted from different reanalyses and starts in 1871.
Vertically integrated water vapor transport (IVT) GIS tool	A python-based function which can automatically calculate water vapor transport at each pressure level and take integral of them. The domain covers the Pacific Ocean, Western US, and Southern Alaska. The tool is suitable for calculating IVTs for the variables extracted from the MERRA and NARR data sets.
WRIT: web-based reanalysis intercomparison tools	A set of web tools for plotting maps and time series that allows users to compare reanalysis and observed data sets.
Climate registry for the assessment of vulnerability	Assessments of the vulnerability of various natural and human resources to a changing climate
Climate resilience toolkit	Enable decision-makers to take action to boost their climate resilience using data-driven tools, information, and subject-matter expertise to make smarter decisions
Planning framework for a climate-resilient economy	Help communities recognize their economic vulnerabilities
Smart growth fixes for climate adaptation and resilience	Codes and policies for climate change

occurrence of precipitation and provides measurements of liquid precipitation and solid precipitation [122].

2.8.2 Radiosonde Temperature and Humidity Sensing

A radiosonde contains atmospheric sensing instrument (e.g., radiometers) installed on a weather balloon to measures different atmospheric parameters and transmission to ground stations. These are generally launched in open seas and ocean for temperature and humidity measurements and provides resolution of up to 10 km depending on the balloon flight altitude and capabilities of sensing instrument [21].

2.8.3 Cloud, Aerosol Polarization and Backscatter LiDAR (CAPABL)

The CAPBL is a tool to measure depolarization, particle orientation, and the backscatter of clouds and aerosols [145].

2.8.4 Operational Bright-Band Snow Level Sensing

A Doppler-effect based atmospheric profiling radar is employed to sense bright band snow levels (the heights in atmosphere at which snow becomes rain) from the atmospheric reflectivity and vertical Doppler velocity [162]. Another type, FM-CW snow level radar, uses advanced low transmit power frequency modulation of continuous waveform technique, which only uses less than a watt of transmitted power. It operates in 2835 MHz frequency band which is useful for precipitation properties measurements due to very weak attenuation/absorption of radio waves by moisture in this frequency spectrum.

2.8.5 Atmosphere Tomography Using Acoustic

In acoustic, travel time of sound waves is measured using array of horizontally located (up to 100 m high) acoustic tomography transmitters and receivers for temperature and wind velocity analysis [168].

2.8.6 Automated Atmospheric River Detection

Atmospheric river (AR) consists of narrow quills of high water vapor transport that leads to flooding [89, 105, 113, 132, 165, 166]. The identification and characterization of atmospheric river events are done using satellite and CALJET aircraft observations in the areas of integrated water vapor and transport (IWV and IVI) [130, 131, 141, 165]. It is based on integrated water vapor thresholds (e.g., width, length, core IWV contents of different features). A comparison of different detection criterion is given in [165]. A list of environmental monitoring systems is given in Table 2.3.

2.9 Case Studies

2.9.1 Indian Ocean Tsunami Warning System

In Indian Ocean tsunami warning system water and wave flow is measured using the whereby kinetic sensors [60]. These sensors are deployed in the ocean bed. These sensors can transmit data from the ocean floor which can be received by disk buoys afloat. The tsunami warnings are issued using these warning systems. The sensors communicate to buoys using acoustic technology for sea floor to surface communications and then use satellite links to warning systems.

2.9.2 Undersea Cables as Seismic Sensors

In an ITU project, sensors are deployed submarine cables to detect earthquakes and seismic events. Moreover, the fiber optic cables, on the ocean floor can also be used as seismic sensors can predict tsunamis, and provide insights into global seismic activity without any disruption to the service [54].

2.9.3 Connected Alarm Systems for Fast Moving Fires

Due to close proximity of home fires can spread quickly in urban slums. A red cross project in high density urban slums is using low cost, low energy, solar power sensors sense and alert authorities about the emerging fast moving fires, its location, and threat. It is deployed in Nairobi and Cape Town [153].

2.9.4 Urban Air Quality Sensing

Air quality sensors are employed to sense air in fresh air in Benin urban areas to track quantity and variations of pollutants. These sensors can sense and sense data with duty cycling period of 20 min using 3G wireless technology [5].

2.9.5 Water Flow Sensors

To monitor hydrological data about river levels and flows, water flow sensors are being used in developing countries. These sonar range water stream sensors can determine the distance to water surface [1].

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Chapter 3
Internet of Things in Agricultural Innovation and Security

Abstract The agricultural Internet of Things (Ag-IoT) paradigm has tremendous potential in transparent integration of underground soil sensing, farm machinery, and sensor-guided irrigation systems with the complex social network of growers, agronomists, crop consultants, and advisors. The aim of the IoT in agricultural innovation and security chapter is to present agricultural IoT research and paradigm to promote sustainable production of safe, healthy, and profitable crop and animal agricultural products. This chapter covers the IoT platform to test optimized management strategies, engage farmer and industry groups, and investigate new and traditional technology drivers that will enhance resilience of the farmers to the socio-environmental changes. A review of state-of-the-art communication architectures and underlying sensing technologies and communication mechanisms is presented with coverage of recent advances in the theory and applications of wireless underground communications. Major challenges in Ag-IoT design and implementation are also discussed.

3.1 Introduction

One of the biggest sustainability challenges of the twenty-first century is to ensure proper food and water to the growing population of the world [140, 182]. Management of these resources is vital in our response to these challenges. The climate change has negatively impacted the agricultural production in last four decades [6, 12, 35, 87, 110, 127, 127]. Various factors such as stresses related to crops, droughts, weeds, crop diseases have caused decline in crop production and yields [45, 67, 85, 93, 119, 129]. Particular, the geographic areas and crops that depend on rain and precipitation are impacted the most due to losses in soil and water related resources caused by extreme weather patterns [121, 132]. These weather patterns are making it hard to adapt to the climate changes in agriculture and stress on critical threshold is already at maximum [86, 122, 206].

The rapid adoption rate in agriculture will be able to keep pace with climate related changes [44, 102, 172, 205]. The innovations in the field of decision agriculture (also called digit, smart, and precision agriculture) are needed to ensure

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global sustainable agriculture and food security [113, 164] through higher crop yields and resource conservation [39, 72, 92]. In the decades to come, sensing and wireless communication in the precision agriculture will play an important role to measure soil moisture accurately over larger landscapes [13, 202]. The accurate soil water content measurements are vital to improve crop yield, better water and irrigation management hence providing food security to our society [4]. Plant productivity also heavily depends on the soil moisture. From the field level to networked landscapes of farms to regional level, there is need to scale point based measurements to remote sensing measurement [161]. Moreover, the lack of interconnection in these measurement paradigms creates errors in models which propagate all the way up to hydrology, vegetation, soil surface, soil saturation, and runoff models [132] and creates challenges for accurate prediction and sustainability over a scale.

3.1.1 Decision Agriculture

The precision agriculture as defined by International Society of Precision Agriculture (ISPA) is [81]:

> a management strategy that gathers, processes, and analyzes temporal, spatial, and individual data and combines it with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability, and sustainability of agricultural production [81].

Recently, for sustainable agricultural practices, the field of precision agriculture has witnessed a lot of development in the areas of technology and concept [8, 25, 42, 64, 107, 142–151, 154–158, 161, 192]. It is beneficial in terms of reduced cost production with high outputs. It is driving in innovations in different agricultural areas such as farm equipment and machinery, crop, plant, and soil sensing, seeding, and harvesting. These technologies in decision agriculture are being used to make informed decisions for sustainable agriculture in real time that helps to reduce input and resource conservation through applications of variable-rate techniques in the field such as variable-rate irrigation. Moreover, the pesticides, fertilizer, and nutrients inputs can be tailored accordingly based on the field conditions. Accordingly, the accurate applications are done for critical areas which leads to economic benefits (e.g., improved crop yields with low cost). Through sensor-guided decisions, the costs reduce at different stages of the crop growth such as types and density of seeds, inter-plant spacing, and planting depth, rates and schedule of fertilizer, pesticide applications, and customized harvesting. The important

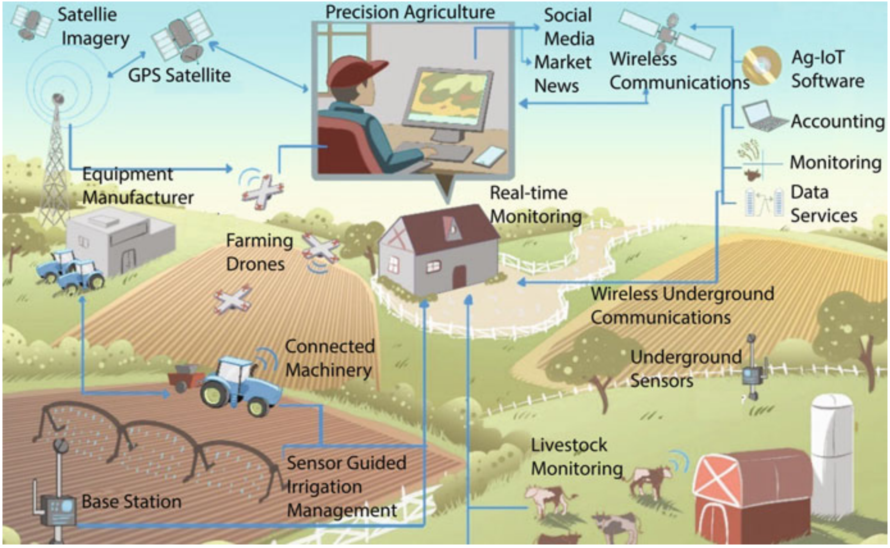

Fig. 3.1 An overview of the precision agriculture technologies

precision agriculture technologies are in situ and remote sensing, geo-location, soil mapping, and variable rate technologies. (see Fig. 3.1). The custom application of seeding, fertilizer, herbicides, chemicals, and pesticides technologies are manual control GPS guidance system, automatic control GPS guidance system [50], automatic control of nozzle and sprayer boom [208], sprayer turn compensation [111], and variable-rate prescription maps [141]. Currently, precision agronomist services available to farmers are soil sampling and field mapping. Soil sampling is done using whole field approach based traditional methods, grid patterns, and through management zones. The management zones for soil sampling are determined by electrical conductivity, and soil mapping unit. The yield dependent field mapping is done using GIS and soil EC, pH sensing, chlorophyll sensors for N, and profit/cost analysis.

3.1.2 Main Barriers to Digital Agriculture Technologies Adoption

There are many barriers to adoptions and expansion of digital agriculture technologies. The precision agriculture technology adoption in maize production is shown in Fig. 3.2. First major issue in adoption is return on investment. Still the cost of digital agriculture equipment and services is higher than the benefits. This also affects the motivation levels of the farmers because there is more emphasis on increasing farm income as compared to adoption of the technology digital agriculture technology

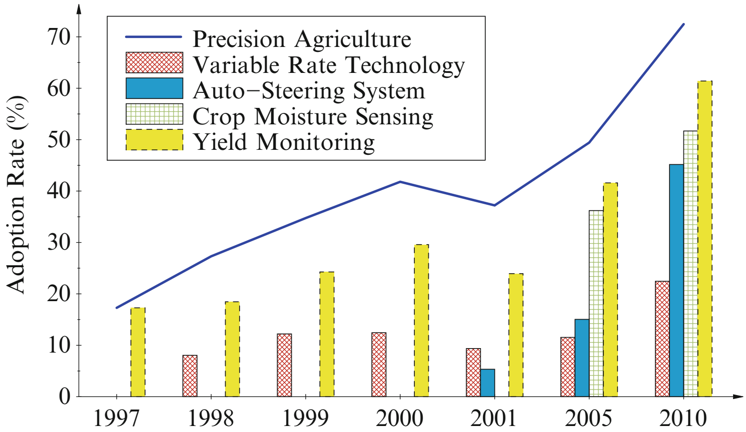

Fig. 3.2 Precision agriculture technology adoption in maize production [202]

business is mostly targeted to the big farms and smaller farm owners are left behind. Moreover, the use of digital agriculture technology in diverse topographic and soil texture fields is milted. Due to enormous data being generated from the farm and lack of decision tools, interception and decision making are very time consuming for the farmers. Farmers trust more the educated guess based on experience rather than having confidence in the recommendations made based on the sensing (in situ and remote), yield maps, and soil maps. Because of these barriers the digital agriculture business is not profitable. The cost and availability of specialists for complex equipment, lack of manufacturer support, difficulty in putting up encompassing high value, precision portfolios are the limiting factors for precision business.

3.2 Internet of Things for Sustainable Agriculture

Internet of Underground Things (IOUT) has numerous applications in the field of digital agriculture [8, 25, 42, 64, 107, 142–151, 154–158, 161, 190, 192]. It is a paradigm in which technology is being used to effectively manage agriculture by understanding the temporal and spatial changes in soil, crop, production, and management through innovative techniques. A multitude of wireless devices is employed for sensing and communications on the field [202] in smart farming. With the development of novel soil sensing methods, adaptive input application (e.g., fertilizer and lime), and soil mapping techniques, there is a higher demand for increased data rates and long-range underground communications. Another important application is in the area of border monitoring, where this technology is being employed for border enforcement and to curtail infiltration [9, 181]. Moreover, IOUT is also being utilized for landslide and pipeline monitoring [64, 179, 180].

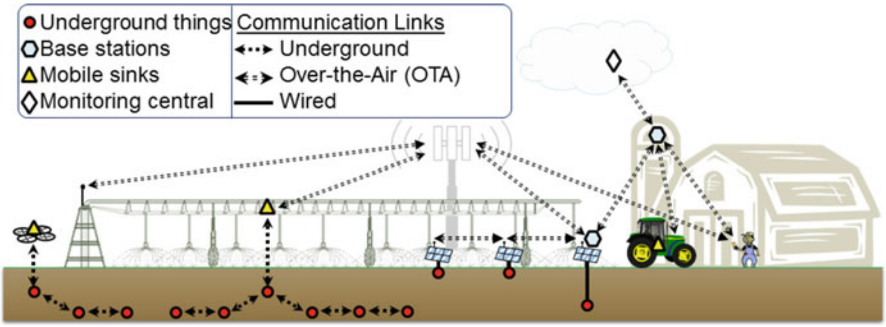

Fig. 3.3 IOUT paradigm in precision agriculture [202]

The IOUT delivers consistent access to data garnered from the farming areas via underground networking, aboveground networks, and the Internet. IOUT Paradigm in precision agriculture is shown in Fig. 3.3. IOUT incorporates in situ underground sensing [4] of soil physical, chemical, and biological factors which includes water content sensing, salinity sensing, pH and nitrogen sensing, and temperature sensing. It also has the communication capabilities built-in as one of the integral components to provide the sensing data from the plants, roots, and the soil. Moreover, it has the ability to include the environmental sensing capability to provide the real-time data pertaining to the diverse environmental phenomena such as wind data, rain information, and solar potential [203]. When integrated with agricultural machinery and farm equipment on the field (e.g., seeding equipment, irrigation controllers, harvesting machines and combines), the IOUT leads to the full self-sufficiency on the smart farming fields, and has the strong potential of development of enhanced food production solutions and applications in the area of digital agriculture [202]. The IOUT is also being utilized to provide useful decision making information to the growers in the field in real time.

The sustainable agricultural-IoT in the subsurface environment has the potential to transform soil and natural resources management systems. The improved knowledge gained through development of this underground sensing system will contribute to the development of better management techniques in the field of digital agriculture. Effective and reliable soil moisture sensing and irrigation management techniques will lead to advances in underground sensing and communication technology. To build technology-aware, advanced digital agriculture practices, this innovation and automation in underground sensing and secure communications, data collection, analysis, and visualization will play a vital role. Based on the IoT systems, sensors for soil and water quality across networked landscapes can be developed. Moreover, it will also facilitate integration of advances in digital agriculture data analytics, in situ and remote sensing into working systems, indigenous and local information.

The development and application of novel sensing and communication techniques for water resource conservation and enhancement of the crop yield is a major

area in need of technology innovations. A large-scale field Ag-IoT built using these wired and wireless technologies and sensing solutions will also aid in advancing the fields of subsurface radio wave propagation, underground communications and networking, and digital agriculture data analytics. It enables novel way of studying soil properties will facilitate efficient resource usage (e.g., improved water conservation, improved crop yield) leading to health and sustainable communities. Creation of networked collection of existing soil type and moisture related databases will improve access to large-scale consolidated data for decision making.

3.3 Wireless Underground Communications

An accurate analysis of wireless underground channel model is vital for any efficient wireless subsurface communications system design. The prospect of completely underground sensing and communications network, without any footprint on the soil surface and support from nodes mounted on aboveground infrastructure, has therefore fueled interest in underground channel propagation measurements. Since many of the smart farming future applications will need high data rate and long-range connectivity between underground and aboveground nodes, a lack of detailed measurements is affecting the design of next generation soil sensing systems [150, 156, 161].

Not only the subsurface path loss as compared to over-the-air (OTA) is higher in the wireless underground channel [41, 144, 152], but also the underground antenna design is highly sensitive to many soil factors such as soil texture, bulk density, soil moisture, depth, and the air-soil interface [157]. Furthermore, at lower frequencies in the underground channel, the time domain channel characteristics such as root mean square (RMS) delay spread and coherence bandwidth of the wireless underground channel are of the utmost importance. Because the underground communication system design is highly dependent on these characteristics to overcome higher path loss due to complex permittivity of the soil and also to achieve higher data rate underground communications [144, 153].

The development of a wireless underground channel path loss model that accounts for the soil type and moisture impact is important because of many factors such as the operation frequency, communications protocol, modulation scheme, network layout, connectivity, and other important operational parameters can be ascertained based on the model. Moreover, to evaluate IOUT solutions, a reliable UG channel model is required. Existing over-the-air (OTA) channel models cannot be used in subsurface communications because of the high path loss that is caused by complex permittivity of the soil in the lossy propagation medium. Moreover, spatial and temporal changes in the soil permittivity also lead to path loss variations, a phenomenon not observed in OTA communications.

Impact of soil moisture variations on permittivity and wavenumber in soil is analyzed in this section. The β_s and β_0 are the phase constants in soil and air, respectively. The λ_s and λ_0 are wavelengths in soil and air. Effects of the change in β_s/β_0 and λ_s/λ_0, parameters with change in soil moisture in silt loam, sandy,

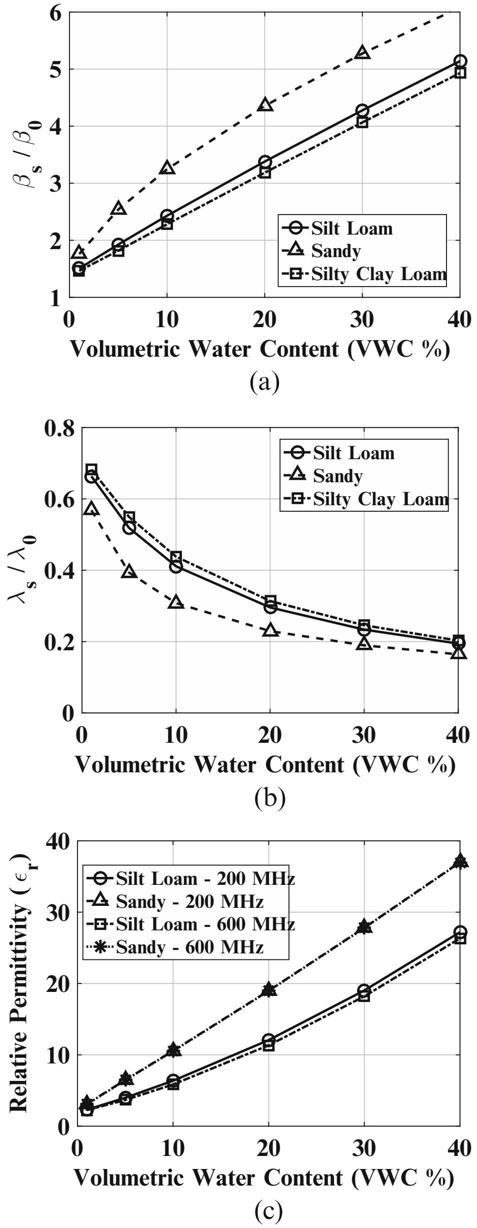

Fig. 3.4 (**a**) Change in β_s/β_0, (**b**) λ_s/λ_0, parameters with change in soil moisture in silt loam, sandy, and silty clay loam soil types, (**c**) Relative permittivity of silt loam and sandy soil with change is soil moisture at 200 and 600 MHz frequency

and silty clay loam soil types, obtained from complex wavenumber $k_s = \beta_s + i\alpha_s$, are shown in Fig. 3.4 (where α_s is the attenuation constant in soil). From Fig. 3.4, it can be observed that β_s/β_0 increases with increase in soil moisture. At 40 % soil moisture level, in silt loam, and silty clay loam soil, phase shift is 5 times higher as compared to the free space β_0. This effect is more significant in the sandy soil.

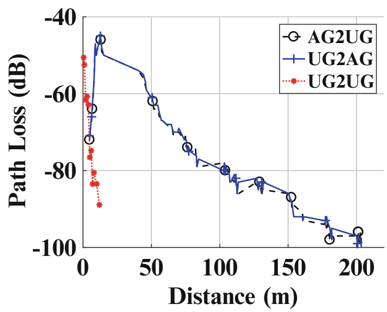

Fig. 3.5 The path loss of different wireless channels in underground communications [202]

Effects of change in wavelength, λ_s/λ_0, as compared to OTA wavelength are shown in Fig. 3.4b. Frequency shift as compared to the OTA is less for lower soil moisture levels, and it increases with increase in soil moisture level. It can be observed that at higher soil moisture levels, due to higher permittivity of the soil, the difference in frequency shift between different soils is also low. In Fig. 3.4c, relative permittivity of silt loam and sandy soil with change in soil moisture at 200 and 600 MHz is shown. It can be seen that change in soil moisture affects the relative permittivity of the soil. Sandy soil has larger effect due to the change of soil moisture as compared to silt loam soil. It can be also observed that sandy soil permittivity does not change with frequency. This is caused by two different physical phenomenon, namely dielectric and conduction losses. Soil moisture variations happens due to dielectric losses in soil as a result of relaxation process of water particles held in the soil medium [40].

There are three different paths that contribute to propagation in wireless underground communications. Through-the-soil paths are direct and reflected. For both components, the wave path remains completely in the soil. The third wave, lateral component, moves along the air-soil interface above the soil surface. The path loss of different wireless channels in underground communications is shown in Fig. 3.5. An in-depth discussion of these components of UG channel is presented in [41, 159].

3.4 Underground Antennas and Beamforming

In [145], an empirical investigation of propagation path loss variations with frequency in sandy and silty clay loam soils has been done using planar and dipole antennas. The path loss experiments are conducted using vector network analyzer (VNA) in sandy soil testbed, and greenhouse outdoor silty clay loam testbed for different operation frequencies and communication distances. The results show that the planar antenna can be used for subsurface communications in a wide range of operation frequencies. The comparison paves the way for development of sensor-guided irrigation system in the field of digital agriculture. Moreover, a model has been developed to predict the resonant frequency of the underground dipole antenna at different soil moisture levels and depths [157]. The textural triangles containing resonant frequencies for all soil types are shown in Fig. 3.6.

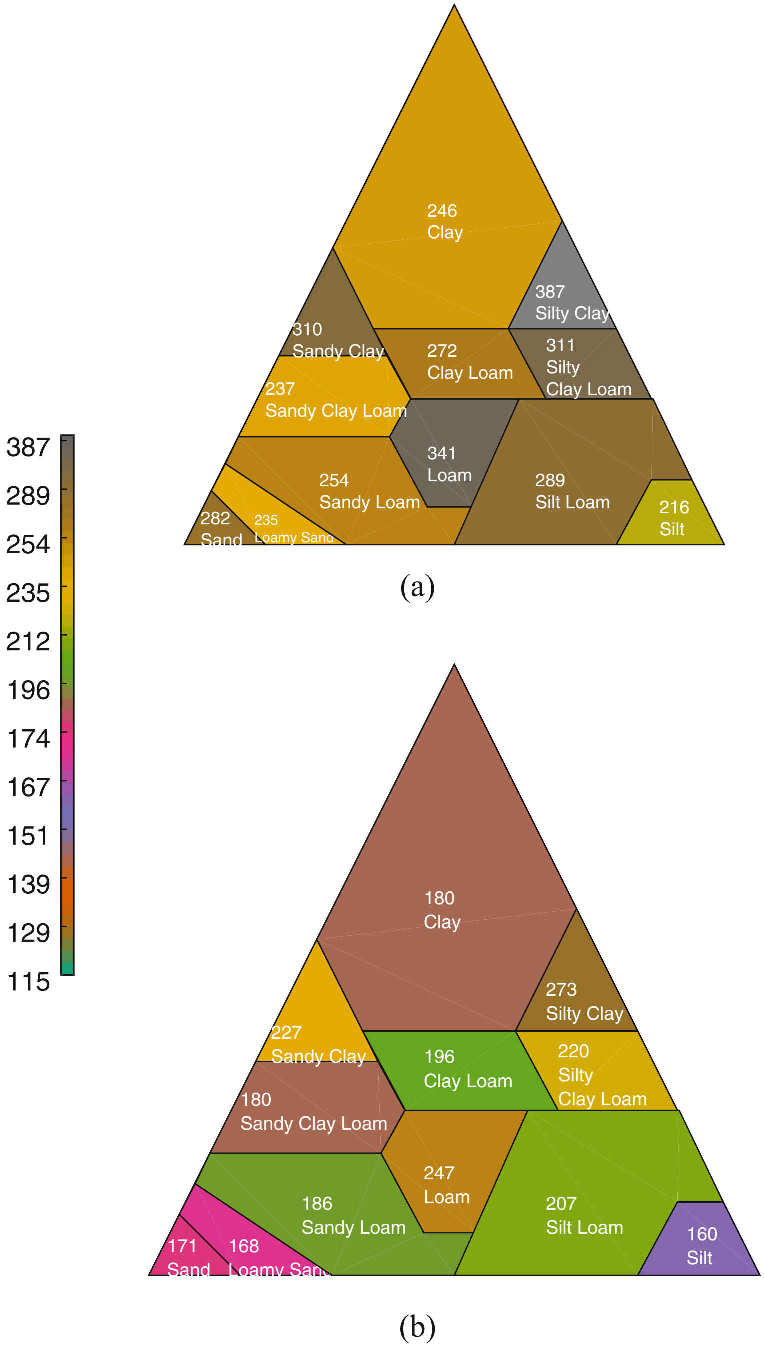

Fig. 3.6 Resonant frequency (MHz) of different soils in textural triangle at different soil moisture levels for a 433 MHz OTA antenna [157]. (**a**) 10% VWC. (**b**) 20% VWC. (**c**) 30% VWC. (**d**) 40% VWC

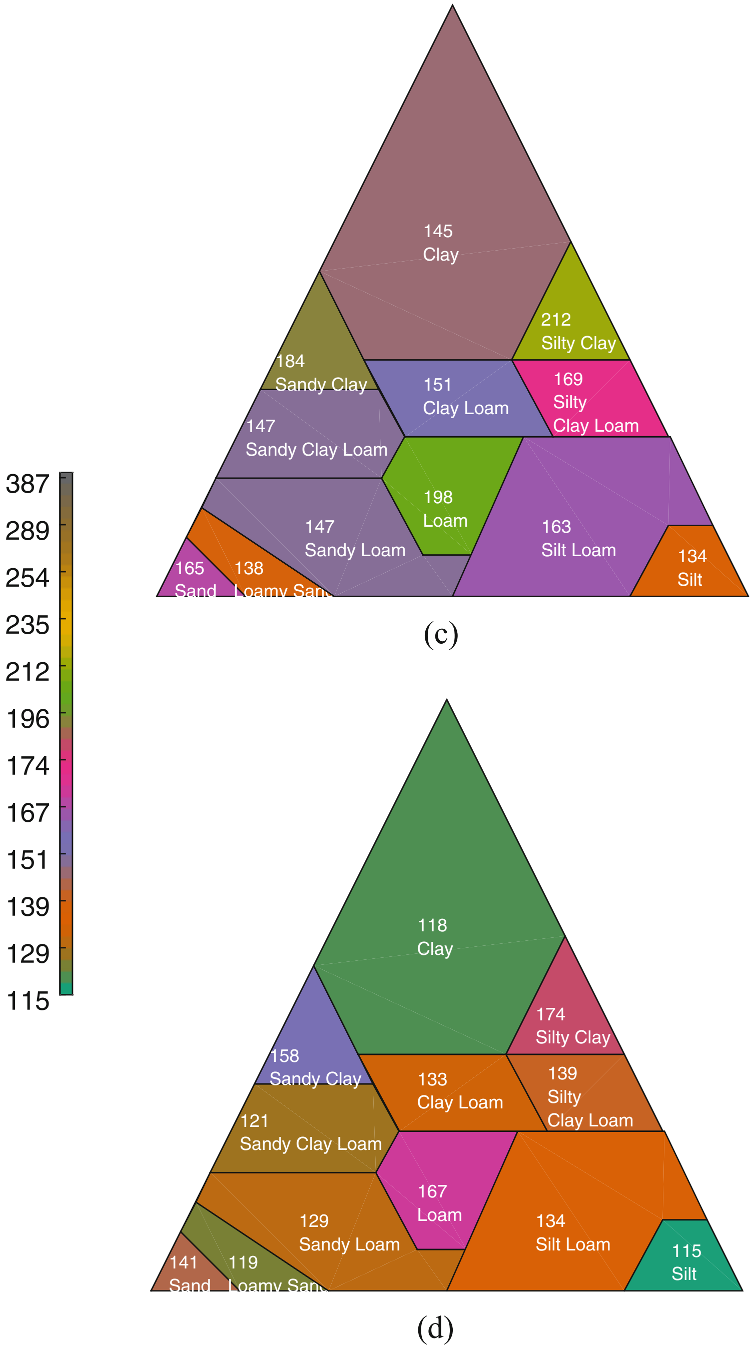

Fig. 3.6 (continued)

The UG transmit beamforming using array antennas at the transmitter can be employed in the underground (UG) communications to maximize the lateral wave by transmitting energy at a particular angle [154, 159]. By using this approach, the energy wastage by sending signals in isotropic direction can be reduced by forming the narrow-width beam and steering it accordingly [198]. In underground wireless communications, the aim is to enhance the received signal strength and reduce the interference at receiver [154]. In underground phased array antennas, the soil moisture adaptive weights, based on soil moisture sensing, feedback signals, are used to adjust the weights by using the array gain feedback loops. This problem is formulated as to maximize the array gain by using the pilot signals. In this method, phased array at the transmitter receives the pilot signal in receive mode and then accordingly adjust its parameters for the transmit mode. In receive mode at the transmitter, scan angles are varied to get the estimate of channel state. The best SNR statistics are used, and accordingly, with change in soil moisture, parameters are adjusted for optimum performance.

3.5 Soil Sensing for Sustainable Ag-IoT

With change in soil structure and particles over time, the process based and empirical models are needed to understand the relation of soil texture with its water cycle [48, 117]. The global climate and change in rain patterns, in addition to the lack of crop rotation, microbes and organic matter, has accelerated the process of changes in pore size, compaction, and structure of soil [131]. The analysis and corresponding analysis will help us to better sensing through the soil communication techniques in response to such biochemical changes in soil [132]. Different factors (e.g., crop and soil type, climate, hydrophilic and bio-geo-chemical properties, pore size evaluation at pedon scale) should be considered together for development of such models. The development of these models will also lead long-term soil sustainability and development of better response to deterioration of soil caused by global climate changes. Currently, there is dearth of novel soil sensing techniques to measure the chemical, biological, and properties of the soil. Accordingly, novel sensing mechanisms are needed to understand these physical, chemical, and biological phenomena in soil. The soil sensing for sustainable Ag-IoT is discussed in this section.

Soil Sensor Requirements The soil moisture and temperature sensors should have the capability to calibrate itself because currently the major challenge in soil moisture measurements is sensor calibration [36, 221, 223]. The understanding of the carbon nutrient cycle, leaching, and uptake process of nitrogen can be improved by development of hydrological flow models. The development of sensors for agricultural purposes should also include to sense salinity and nutrients. The di-electric based and electrophoretic nitrate based signal processing approaches [124] are of particular interest to enhance the soil sensing capabilities for agricultural

applications. The pH and measurements of dissolved oxygen need to be integrated with low-cost low-power systems, advanced power management on single circuit boards [30, 219].

The energy conservation issues are also important in the development of such sensor systems. For prolonged uninterrupted operation soil, these sensor systems should have the capability to harvest the energy from the environment as well as able to wirelessly receive power from soil surface and other aboveground sources (recharge). This wireless transmission of power to these sensing systems can be achieved through the propagation of subsurface radio frequency transverse magnetic mode (TM) where soil-air interface serves as a waveguide. The performance efficiency of this scheme can be increased twofold by using multiple transmitters on and below the soil-air interface, creating two such modes hence maximizing transfer using lateral (Zenneck) waves.

Different sensing and modeling approaches (e.g., remote sensing, field scale tools, in situ sensing, crop models and coefficients, transport models, nutrients and microbes, subsurface soil data) also need to be integrated in the digital agriculture. It will improve our understanding of the physical, chemical, and biological processes of the soil and will also improve soil-crop management practices and health.

Self-Deploying Sensors There is also a need of further development of sensors with self-boring capability to overcome installation challenges in excavation, penetration, and replacement of sensors in heterogeneous environments [99]. The use of robots is a potential candidate for the development and auto deployment of these with this capability with minimum soil and crop during the growing season aided with GPS technology. The major advantage of this approach is ability to auto relocate sensors without human innervation for spatial temporal sensing of physical, chemical, and biological properties of the soil. The major challenges in self-deploying and relocating sensors are ability to adjust to varying field terrain, maintaining connectivity within the optimal deployment region and requirement of different deployment hardware for different type of soils.

Acoustic Soil Sensors Acoustic soil sensors is also being envisioned as the alternative to the wire based sensor techniques [116]. One major limitation of wire based sensors is that low sensor density per unit in agricultural fields as limited number of wires can be connected from the underground hole. Because of the changes in the surrounding environment of these sensors, these connections become gradually weak which leads to loss of connectivity due to cable degradation. Moreover, these exposed cables also offer an attractive target to field animals. Acoustic connections offer opportunity to remove these cables completely for underground to aboveground communications. However, the major challenges in this area are higher path loss because of the higher soil moisture content. Moreover, currently only sea based underwater acoustic and through the animal tissue acoustics communication techniques are being applied and there is need to tailor these underwater communication techniques to groundwater, soil moisture, pesticide chemicals, agricultural machinery, farm equipment, and foot traffic [23, 173, 186, 201]. The

surface acoustic wave sensors can be used to manufacture soil nutrients sensors by using acoustic wave delay lines [103] and polymer based conductive impedance detectors [168].

Seismometers in Soil A related approach is based upon the use of the soundscapes and seismic signals by using the seismometers to study the movement of soil particles [137]. The main challenge in this approach is to pick the signal of interest (elastic waves) form the background noise by using state-of-the-art seismic arrays in geological, ecological, and biological landscapes. These type of measurements because of their high temporal and spatial resolution can provide insights into the different geomorphic bioturbation factors contributing to spoil erosion and landscape changes on surface (e.g., animals, plants, deposit rocks, foot and machinery traffic).

Root Sensing New non-invasive soil sensor systems are needed to understand the root chemistry. Using current methods this information cannot be obtained without disturbing soil. Development of root sensors will make available the real-time information about roots which can be used to model the impacts of soil type and irrigation cycle on the root growth [178]. Current practices for soil root imaging include minirhizotrons [183] and planar optodes [100]. In the first approach, a transparent plastic tube is buried into the soil root growth zone to obtain contusion images of plant roots. The later approach is based on the use of optical fluoresce sensing mechanism [7]. The big size and high deployment cost of these approaches are major factors limiting the use of these techniques in precision agriculture. Moreover, it can also be used at small-scale plant based level. To address these challenges there is need of development EM-based root imaging and growth sensing techniques that can be used at large scale in a cost effective way.

On-the-Go Soil Sensors Depending on the soil minerals and texture, there is an emission of gamma radiation based on the radioactive decay in soil. Gamma radiation is the electromagnetic photons in the visible light spectrum. These are also being used at top soil mapping. However, these cannot be used as real time on-the-go sensing apparatus in soil because one measurement is not sufficient rather multiple measurements are required. The soil pH can also be used to real-time on-the-go soil mapping [4, 5, 171]. A soil pH based autonomous soil sampling and mapping system has been developed in [171] that used ion-selective electrodes technology for pH sensing and soil mapping. The prototype has demonstrated the effectiveness of the system for lime application. A lime is a soil supplement developed from chalk and limestone. There is also need of sensors to measure mechanical impedance of the soil [5]. This mechanical resistance can be used for selection of no-till or chiseled soil treatment based on the soil impedance measurements.

Topography Soil Sensors There is need of development of topography soil sensors for precision agriculture application. The topography soil sensors in the field can be used to measure slop and corresponding water flow. Currently GPS and LIDAR technologies are being used for mapping topography of soil [162].

Microbial Sensors There are many different species of microbes present in the soil ecosystem. These organisms play a vital role in our support system. Development of new sensing approaches can provide us with the better capability into crop growth control cycle and energy influx. In literature, there is no existing work to support the use of microbes as an input parameters into major models (e.g., waste management, soil health, and climate), therefore there is need of inexpensive, real time, capable of highly dense deployment of microbial sensors [26]. Development of new microbial sensing techniques will help in development of better soil models coupled with maximum entropy production from the thermodynamic perspective. It can also provide much needed insights into the microbe organization and composition changes.

The other major candidates for development of novel microbial sensing approaches are methanogenesis, thermodynamically controlled metabolic sensing approach, chronoamperometry, methanthropy, electrochemical and piezoelectric quartz crystal micro-balance (E-QCM) [54]. A network of microbial sensors working together for sensing will improve the reliability and will contribute to decreasing the cost and amount of field inputs in the field of digital agriculture. It can also lead to better crop health. Because, currently, excess or improper application of fertilizers in agricultural fields is causing nitrogen runoff, which not only contaminates drinking water but is creating troubles for commercial sector (e.g., tourism and fishing) [138]. The algae outbreak and reduction of dissolved water oxygen also results from over-fertilization [59, 114]. The phosphorous cycle is also important for sustainable agriculture. The increase in human activity in the field leads to development of hazardous phosphorous in environment. Therefore, growers can benefits through these advanced soil nutrient sensing systems by application of correct amount of fertilizers.

Soil Nutrient Sensing The soil nitrogen sensing techniques require high field density for correct prediction and development of nitrogen models. Moreover, for better accuracy these sensors should be buried at different depths in the soil. Development of low-cost sensors to sense the concentration levels of nitrate, heavy metal ions, and ammonium will help to overcome these challenges. Carbon based low-cost graphene (ionosphere membranes) can be used to fabricate these sensors in a cost effective way to detect nitrate and ammonium in soil [189]. This knowledge along with NDVI will help in improving crop productivity.

The process of soil erosion can be understood and effective mitigation approaches can be developed by sensing soil iron and oxygen. The erosion of topsoil by physical tillage, wind, climate change, and forces of water is a major issue in agriculture [48, 212]. Better insight into the erosion process can be gained from interaction of soil with iron and oxygen. The information combined with surface water lateral flow models can also illuminate the interaction of microorganisms and resulting seismic change in soil chemistry in managed and unmanaged soil.

Photonic Sensors Macro fabricated photonic sensors work on the principle of detecting changes to the environmental reflective index and can be used to measure

soil nutrients. Photo or electron beam lithography based photonic sensors developed on silicon can be used to detect the nitrate and phosphate [10]. This approach has been used in metal sensing but can be tailored to soil nutrients sensing. Zinc oxide nanorods allow spatial high resolution sensing of soil nutrients. These nanorods when combined with Raman spectroscopy can provide highly reliable soil nutrient sensing for abundant and rare nutrients in soil. The major challenges in this area are difficulty in developing standard methods for sensing, calibration, and validation across different nutrient types and soils.

Biosensors Another potential approach for sensing the presence of hazardous microorganisms and chemicals is based on engineered bacterial spores (complete cell-sensors) [106]. Traditionally spores can be used to store biosensors for extended period of time. These biosensors can sense microbial activity based on bacteria can be tailored to adopt to change in the microbial activity in soil. These can be muted as well (dormant mode) and be reused across different sensing cycles. The self-sustainability of these biosensors is an important challenge to achieve long-term field operation to monitor crop health. The underground microbial fuel cell (MFC) is being used effectively to supply power to these sensors [222]. The impedance spectroscopy sensors (ISS) [94] can also be developed by using the MFCs. The ISS sensors are based on detection of change of permittivity of soil to detect ionic concentrations in soil. Therefore, it can be used to monitor the soil nutrients. However, there is need to develop and validate models to connect these permittivity changes to microbial activity and changes in soil.

Micro-Electro Mechanical System (MEMS) Array The soil health can be better characterized by bio-chemical processes and volatile organic compounds produced by them. The detection of soil chemical properties is currently restricted to the pH. The micro-electro mechanical system technology consists of miniature transducers which can be used to sense concentrations of these chemicals at different frequencies. These combined with other sensors can provide a full spectrum soil health sensing capability in digital agriculture. A schematic of the cantilever-array nutrients sensor is shown in Fig. 3.7.

Soil Organic Matter Sensing The soil organic matter (SOM) constitutes the 2% of the soil particles but is not generally accounted as part of the soil texture, which sometimes lead to error in soil models. The sensing of the subsurface biotic factors (e.g., plants, algae, animals, bacteria, and fungi) and abiotic factors (e.g., soil type, mineral weathering, temperature, soil water content, sunlight, oxygen present in the soil pore space, wind speed, water flux, carbon nitrogen cycle, carbon dioxide, ammonia, and nutrients) can provide decision making information in the real time. Among these the soil respiratory quotient (RQ) [29] is a strong indicator of soil metabolism. An understanding of water-gas exchange and diffusion can also provide better information into the gases composition in soil. The pore space sensing for presence of azane, carbon dioxide, and oxygen can be used to assess nitrification process, gas water exchange, and diffusion in different soil textures. Variation in these also need to be investigated over large spatial and temporal scale in agricultural fields.

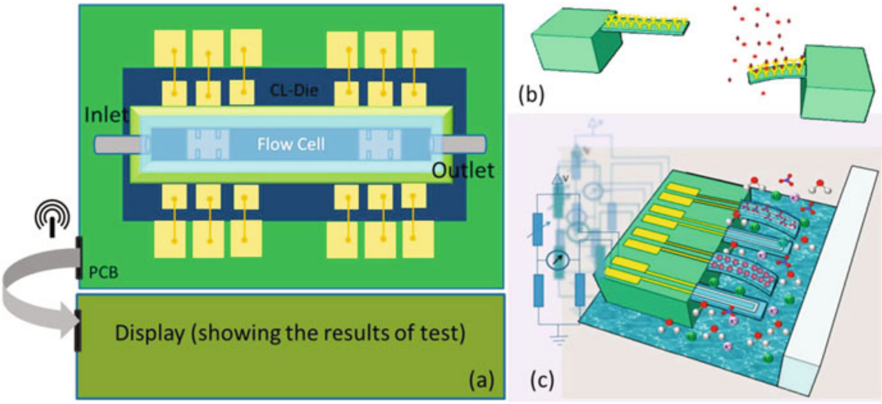

Fig. 3.7 A schematic of the cantilever-array nutrients sensor [125], (**a**) a lab-on-a-chip system (LOC), (**b**) sensing principle of a micro cantilever, (**c**) microcantilever array depicting the sensing of multiple macronutrients

Stress Sensing The lack of enough nutrients, water shortage, improper irrigation, crop diseases, and weeds leads to crop stress. Proper identification of factors causing the crop stresses is vital for insights into phenology and crop physiology. The multi-spectral and hyper-spectral sensing approaches can be used chlorophyll concentration sensing and biomass estimation. However, systematic research and empirical evaluations in the areas of multiple view plant geometry and RGB are required to show effectiveness of these approaches in crop stress identification.

Weed Sensing The weed sensing is another area of digital agriculture that requires major research because weeds have a significant impact on the crop yield. The satellite based imaging for weed sensing has not been promising because of low accuracy, reliability, and resolution. Therefore, new techniques need to be developed for GPS guided high resolution to effectively sense different types of weeds. High quality weeds map can help identification, classification, and proper elimination of weeds.

Autonomous Disease Sensing There is almost total lack of literature on use of technology in digital agriculture for autonomous disease detection. Although the problem of disease sensing has been investigated from the vegetation index perspective by comparing and contrasting the normal and anomalous crop growth pattern. However, models are required which can link these abnormalities to the automatic early stage disease identification.

Plant Temperature and Physiological Properties Sensing The vital physiological properties of the plants can be estimated through the chlorophyll fluorescence sensing. It requires light-saturating photosystem technology with high beam intensity. Lasers that can produce this high intensity beam cannot be used for plants. Traditionally, satellite imagery has been used for chlorophyll fluorescence sensing but suffers from low resolution problems. Another alternative is micro-hyperspectral

sensing technology. However, it is expensive and it is not possible to use it for large farms. Therefore, novel inexpensive fine resolution chlorophyll fluorescence sensing techniques need to be developed.

The plant temperature sensing via thermal sensing is done to assess the water stress. This sensing is important to analyze the important process of photosynthesis. Thermal sensors offer very low resolutions and have to be placed close to the plant for correct assessment of water stress. By mounting un-cooled thermal sensors on mobile farm machinery can lead to this assessment but it is not possible for all crop types. But it results in slowing the speed of that particular machinery on which these sensors are mounted, because an instantaneous thermal sensor imagery cannot be used to measure water stress. Rather multiple images are required which are then processed off-line to assess water shortage. Therefore, advanced technology is required for real-time in situ processing of the data and estimation of deficiency of water pressure and CWSI. Moreover, interferences (e.g., the machinery heat generated from the field operation, soil emissions, and plant temperature) are some of challenges that limit applications of this approach to the field of the precision agriculture.

3.6 Aerial Sensing

In digital agriculture, UAVs are becoming ubiquitous as an IoT platform for sensing, data collection, and real-time decision making. Because of flexible design and lower footprint, these can be adopted for use in different types of fields in different terrains UAVs are high quality, inexpensive, higher resolution, and high rate data collection as compared to the remote sensing where performance suffers from the bad weather conditions. Other advantages of UAVs in precision agriculture are ability to select and integrate different sensors on the UAV In terms of modeling, UAVs offer better alternatives to the traditional agricultural modeling processes. Potential applications of UAVs are monitoring the nitrogen status for building nutritional nitrogen index and map, and evaluation of crop growth during the growing season using regression for making SAVI, NDVI, NDRE index indicators of vegetation growth UAVs in precision agriculture is also being used for plant height and biomass analysis with very higher accuracy using multiple UAV trips in the field in real time. The approach of photogrammetry is very helpful for this types of height analysis. A detailed analysis of this approach has been presented in [70]. A stand count analysis in crop field via UAV photos combined with proximal soil sensing and satellite photos has been done. Digital agriculture can be benefited from automation of UAV flights for safe operation, integration of different sensors and sensing techniques across disciplines under a standard protocol, and development of business planning models and supervised learning for effective and optimum field operation. Other novel applications of UAVs include disease and water stress and weed detection, biomass and yield prediction, assessment of deficiency of nutrients, and crop modeling and classification.

The crop ripeness and weed analysis using UAVS have been done in [70] for prolonged field operation and predictive models have been done based on this analysis. In [177], UAVs are utilized, in cotton fields, for canopy response observation and residue management using a thermal camera mounted on the craft. The nitrogen and correlation of LAI and biomass have been analyzed using different UAVs in [14, 71, 75, 184, 197]. Applications to the effective in-field irrigation management and soil sensing using UAVS are shown in [3, 62]. The idea of multiple micro UAV platoons has been presented in [62]. The use of UAVs for fertilizer management in the crop field has been done in [76, 118]. The superior capabilities of spatio-temporal sensing of the UAVs as compared to the remote sensing are demonstrated in [20, 22, 165] using thermal and multi-spectral sensing systems mounted on UAVs. The correlation between the remotely sensed soil moisture and in situ soil moisture measurements is done in [18]. The analysis of plant structure and canopy and plant height was carried out in [11, 95, 218]. In [218], the drainage management has been done using crop scouting. Plant pathogen mapping using UAVs has been done in [120, 188] in a potato field. Applications of UAVs in the area of canopy cover and temperature are tested in [21, 109]. The weed detection and management using UAVs have been explored in [37, 53, 60, 74, 126, 174, 193]. The effectiveness of the crop disease detection using UAVs has been studied in [28, 163, 176]. The characterization of plant growth parameters and yield prediction has been done in [15, 57]. The biological and physical parameters of the soil were estimated using UAVs in [217]. The application of UAVs in the area of vegetation maps and for creating different Indices (NDVI, LAI, GAI, GNDVI, CWSSI, PCRI) using UAVs have been carried out in [27, 56, 108, 194, 199]. Use of UAV imaging in precision agriculture has been discussed in great details in [2, 51, 56, 58, 73, 97, 101, 108, 120, 211]. A detailed analysis of UAV based pest management has been done in [133].

3.7 Big Data

The decision making parameters at the farm includes nitrogen, P and K, liming, hybrid variety selection, placement in field, crop planting rates, variable seeding rate prescriptions, pesticide selection (e.g., herbicides, insecticides, fungicides), cropping sequence/rotation, and irrigation. The data obtained from soil testing, yield and soil maps, EC at farm level and through satellites. It can be managed at different levels. At local level, the data obtained from farmer is restricted to farmer use only at the field level and no data aggregation is done. At the farm level, data is aggregated from different fields within the farm. At regional level, data collected from the farmers can be combined for effective to get regional insights These data collected at the regional level can be combined to national level decision making and can also be used in analysis of the future trends [19, 169].

3.8 Soil Mapping

Soil mapping holds high promise in the area of digital agriculture for production of high quality high resolution soil maps. Through soil mapping impact of different physical, chemical, biological phenomena on the crop and yield can be assessed [112]. The production potential of the soil can be correlated with plant growth and seeding can be adjusted accordingly. Effects of fertilizer can be assessed using soil maps to make adjustments to inputs accordingly. The loss of nitrogen can be controlled to improve yield. Some basic components of the soil mapping are soil texture (percentage of clay, slit, and sand) mapping, salinity, soil organic matter mapping (OM), curvature, slope, tomography, and TWI.

Currently, electrical conductivity, optical, topography, gamma, and electromechanical sensors are being used for soil mapping [61, 63]. The soil salinity and texture sensors work by measuring the in situ electrical conductivity of the soil and are based on the ability of soil to conduct electricity. The clay soils have the higher conductivity because of the presence of significant amount of the fine clay particles. On the other hand sandy and silty soils have particles in large size. Therefore, their ability conduct electricity is low as compared clay soils. The measurements electrical conductivity measurement differences are used to map soil texture. The electromagnetic induction and soil contact are popular EC methods. In soil contact EC measurement method, sensors work in contact with the soil using EM wave, whereas MI sensors work on the principle of induction. Both methods have comparable results.

Soil texture mapping using EC has many advantages: 1) crop growth is directly related to the soil texture water holding capability of soils also depends on soil texture. Clay and silty soils have higher water holding capacity as compared to the sandy soil because of the number of the pores and pore size difference [49]. The root depth and other soil properties such as cation exchange capacity (CEC) also depend on the soil texture. Soil mapping is also used to characterize the soil response to the applied herbicides. Soil animal population, transport of nutrients, and buffering capacity are soil factors vital for crop production and growth. The major application of soil maps generated through soil sampling is in demarcation of soils in different zones, variable rate seeding and sowing rates, assessment and management of nitrogen, and yield maps. These maps combined with output of other soil sensing mechanisms lead to creation of comprehensive real-time decision making tool.

Moreover, the soil EC can also be calibrated with soil type with laser diffraction mechanisms. It also guides soil sensor location, and density in the soil for sensor guided irrigation management in the field thus leading to optimum operation. In the regions with high soil variability soil maps are proven useful in development of seeding plans [16].

Organic carbon and matter sensing can be carried out using optical reflectance [209] to distinguish between organic matter and carbon. An agricultural field with

darker color soil texture has higher amounts of organic matter as compared to lighter color textured soils. This phenomena is caused by the absorption and bonding of light with CH and OH molecules of the soil which leads to darker colored soils in with at presence of higher organic level and high soil water content. In soil maps these areas also appear darker. However, the current ability of these soil mapping systems is milted up to top inch of organic matter. On the other hand organic matter layers can be 2–3 inch deep in some soils. Therefore, development of optical soil sensing techniques with ability to generate layered soil maps below 2–3 inches is very essential. Because soil organic matter improves soil aggregation, helps in mineralization of N, P, and S, expedite the nutrient exchange process, reduce the top soil crusting process, and prolongs the soil water content retention in soil, and reduces soil compaction and bulk density. Given this important nature of the organic matter, the OM soil maps can be used as good indicator of the soil health and increase OM understanding. These can also aid in nitrogen management, and variable rate seeding. These can also be related to other soil parameters, EC, and nitrogen soil models for informed decision making.

The results from multitude of available soil mapping approaches discussed in this section can be used powerful with fused sensor data using multiple soil layers. These multi-layer soil maps are important to understand and get insights about what the change, what caused it, and what is the best course of action to deal with it [17]. In precision farming, existing challenges in adoption of soil mapping approaches and resulting maps are limited motivation to use them because lack of high precision maps. Moreover, in practice, fixed application of lime, K, and p is carried out, and relationship of the insights gained from the yield is not very strong. Now with the availability of high precision maps the inputs are indirectly dependent on the soil texture and growers are customizing there application of fertilizer based on the maps that leads to improvement in crop yield as well. Creating these soil maps is becoming more convenient with improved technology and ubiquitous connectivity. With the success of variable seeding and fertilizer application, there is need for high precision soil maps to inform these variable technologies.

3.9 Digital Agriculture Education

There are many climate and production differences (e.g., crops, water availability, irrigation practices terrain) between the different regions of the world. This contrast leads to differences crop yield, return on investment for the same crop in different regions. Therefore, precision farming education and curriculum should be designed accordingly [151].

3.9.1 Curriculum Development

For precision agriculture curriculum, the leonine courses should be available to growers, policy makers, farm managers, and workers in order to provide training on latest developments. These training sessions can also be conducted on campus in evening and on Saturdays to attract larger agricultural community. Government funding can help to start these initiatives to train and certify digital agriculture workforce. Universities in consultation with the industry partners and Ag companies can develop course plans for students. Availability of internships in this area will aid in creation of skilled workers for jobs. For farm mangers, one such sequence of courses can combine latest developments in irrigation management, food sciences, with advanced precision agricultural technology. Other major digital agriculture areas needing attention are integrated management of pests, training in safety, and use of connected heavy machinery and equipment. Although many community colleges in USA are offering training in these areas but with the rapid developments and advances in technology the institution of higher education should assume the role of training the next generation of students to adopt digital agricultural careers. Universities can not only conduct research but also transfer it to the community through start-ups and partnering with industry.

These connections can help students to learn the current needs of industry, the direction in which market is proceeding, and current precision agricultural use-case. These partnerships will also help to build focused faculty research groups and labs, and will make huge advancements in the field through integration of ideas. The existence of novel challenges and right opportunities will increase the motivation to work together to find solutions and technology transfer. The industry board from precision agriculture company will help shape the overall curriculum learning objectives through technology updates, discussions, and feedback. Through classroom integration curriculum can be enriched with examples, industry based capstone design projects. Through this hands-on training student will learn better about new developments in the area. Internships in digital agricultural companies though meaningful projects will also contribute to digital agriculture workforce development and create new employment opportunities at all level for students, industry, and academia. Overall, these university-industry partners can together solve many challenges in the area of silage and grain covers, underslab gas barriers, fumigation, building enclosures and landfill covers.

The precision agriculture curriculum should be viewed as multidisciplinary tree have branches in agronomy, computer science and electrical engineering, sensor technology and sensing approaches, biological sciences and engineering with one shared goal of increasing crop yield though reducing input cost, better management and informed decision, and sustainable agriculture practices. The propose of the digital agriculture curriculum should be able to develop global leaders for solving great changes in the area with a common commitment to future of digital agriculture. It will benefit farm mangers, software developers, agronomists,

engineers and technicians, and educators. It requires dedicated efforts by providing more resources, reducing adoption barriers to precision agriculture technologies, and investing in industry academia partnerships.

3.9.2 Work Roles in Digital Agriculture

The precision agriculture work roles are described below:

- An applicator is the field worker who works to apply fertilizer and pesticides by using the related equipment.
- An agronomist specializes in soil and crop management, and provide recommendation to the farmers.
- A precision equipment technician is expert in digital agriculture equipment installation, trouble shooting, repair and maintenance on the field.
- A precision sales specialist deals with sale and support of digital agriculture equipment and software. In this role, a precision sales specialist can also provide services remotely.
- A data manager collects and analyses data from customers, farms, and agriculture businesses.

3.10 Energy Harvesting

For sustainable underground soil sensing and field communications operation, it is highly desirable to transfer wireless power to subsurface radios and sensors. In the agriculture field, ideally, the lifetime all sensing equipment should be greater than 5 years [78]. With the recent developments and improvements in technology and through development of energy efficient sensor materials, the energy requirements for these sensors are decreasing rapidly. However, underground radios still require power to communicate through the soil to aboveground receivers. There are many intermittent energy harvesting resources available on the field for precision agriculture that includes solar, vibration, bacteria as fuel cells, thermal, underground living plants. However, the literature is scarce on underground wireless RF power transfer. The maintenance, repair, removal of sensors for battery replacement, and re-installation of underground equipment is costly and access to field equipment are sometimes not only difficult and also causes disturbance to soil and plants. The extended lifetime of digital equipment is very important adoption of the technology in precision agriculture.

In the digital agriculture, these underground devices can be powered in many different ways. The first method is based on wireless power transfer and is based on EM induction and magnetic resonance [68], and radiation.

Through RF power transfer energy can be transferred from source to the subsurface equipment using the wireless electromagnetic waves. These waves exhibit less deterioration and attenuation as compared to resonance and induction based approaches. Therefore, it can be used for long distance (up to few meters) energy transfer [31]. The normal power consumption of underground devices is few milliwatts. Since, underground digital agricultural devices can operate with low power using duty cycling. In duty cycling, the sensors and radio are activated only when sensing data and communication is required. In a large farm, the sleep time can vary from few hours to days depending on the growing season, climate, and irrigation needs. For remaining time the nodes remain in the sleep mode. Therefore, even few micro-watts power is sufficient for sustainable operation in the agricultural fields [91, 213].

Wireless RF power transfer requires external sources. The power beacons can be developed and utilized for this purpose. However, in the field it is hard to have fixed aboveground energy sources as power beacons permanently dedicated to power the sensors and radios. However, these sources can be mounted on pick-up trucks and farm equipment such as tractors. Moreover, the UAVs can be used to install these external power source combined with other data collection and sensing equipment for concurrent information and power transfer. Novel methods need to be developed for external energy transfer. The power transfer through the soil should be investigated. The ideal depth of sensors and distance between different nodes can be modeled by understanding the deterioration of signals in the soil. A detailed survey of power transfer in over-the-air wireless communications and networks has been given in [104, 105]. External power sources can be designed based on a single antenna approach where energy can be transferred to single node only. However, recently, the idea of using multi-antenna approaches has attracted the attention of the research community, where the beamforming can be used to direct energy to multiple nodes by using the beamforming.

3.10.1 In Situ Energy Harvesting Methods

This interaction with the external power sources can be avoided with the development of in situ energy harvesting methods. The second method is based on energy harvesting from different sources. The piezoelectric technology has the capability to convert the vibration energy into the power. It can be modeled through circuit and mechanical methods (mass, spring, and damper) [89, 216]. However, this technique required to correct vibration frequency in order for power generation. The operation of diverse equipment and traffic leads to generation of different frequencies in the field. Therefore, either the multiple vibration sensors tuned to different frequencies, or one sensor with broadband spectrum sensing capability is needed [66, 123]. In [89], the applications of vibration energy harvesting has been investigated in a corn field. Through the use of piezoelectric energy harvesting technology, where these devices are buried in the field at low depths, has been used to harness the vibration

field sources (e.g., the seeders, farm machinery, and harvester, combine and other agricultural equipment). This empirical analysis has shown the viability of this technique for digital agriculture. However, the provision of prolonged sustainable energy to underground sensors is still challenging because this method is not sufficient to provide power to multitude of devices underground. The burial depth of the equipment is one major issue because at deeper depths attenuation is higher in the soil. To overcome challenges in the area of energy harvesting in the field, more insights into the vibration propagation in soil are needed. There is also need for development of new protocols and platforms for subsurface power transfer. The link layer protocols for optimal frequency section and sensor placement should be developed. An in-depth validation of these approaches is required at the field level with consideration of models, non-linear efficiency, power consumption of circuits. It should also be combined with novel channel estimations methods in underground communications.

3.10.2 Wireless Subsurface Power Transfer

Generally, agriculture fields do not have enough ambient RF energy (stray EM waves) that can be harvested for self-sustainable operation. Another method is based on the use of energy harvesting for received data communications signals. It is done either through time sharing approach, where some slots are allocated to information transfer and alternative time slots are assigned to RF energy sensors. Other approach is based on frequency sharing, where frequency of the information signal is shared with the RF energy harvester. Beam splitting is another method for distribution of energy via energy scheduling approach. These co-channel data and power transfer approaches have been investigated in [31, 32, 135]. However, it leads to information communication performance degradation and required designing new equipment which increase the cost of deployment hence increasing the challenges in digital agriculture adoption.

There is also need of medium access protocol (MAC [52]) for RF energy transfer techniques to work for multiple users in wireless underground network [115]. A rectenna is a type of energy harvesting antenna which is used for collection and rectification of the EM waves [136]. Many technologies are available to manufacture a rectenna for use in digital agriculture applications. These include CMOS, tunnel, Schottky and spin diodes, and active rectification. These rectennas also required matching circuits to match the input impedance of the rectifier to the impedance of the antenna for maximum energy harvesting. Design of such antennas has been explored in [47], that can be tailored for underground RF energy transfer applications. Some field experiments using these antennas in bridge settings are done in [47, 79]. Further investigation of possible distance up to which RF power can be transferred should be investigated as power transfer efficiency is dependent on the distance. There is also need of development of energy beamforming with adaptive steering towards any underground and aboveground nodes. Because with the advancement and adoption of precision agriculture practices, a multitude of sensors

will be deployed across the field. The use of multiple antennas in the aboveground power source can be used to achieve very narrow-width beams with capability to carry more power as compared to traditional single antenna transmission. For beamforming with beam steering capability to work, there is need of accurate channel estimation of underground channel between transmitter-receiver pairs to obtain the channel gains. The wireless underground channel impulse response can be utilized for this purpose [160].

Additionally, the traditional receiver guided [207, 215] and up-link phase estimation approaches can be used. To reduce the equipment complexity and to conserve energy there is need of development low complexity channel estimation schemes based on the receive power only (e.g., one bit feedback algorithm) [214]. Moreover, in agricultural Internet of Things (Ag-IoT), an energy neutral operation [175] is desirable to avoid the saved energy from being depleted and also to attain high efficiency of energy transfer and harvesting schemes. Duty cycling of the underground can be utilized as well to conserve energy. This depends on many factors such as requirement of frequency sensing operation, distance from the external power sources, crop, fertilizer inputs, and weather [170, 204]. Duty cycling can be activated based on some threshold of power going below some level and system should also have the ability to automatically make changes on the sleep and wake-up duration based on the changes in these field factors. Moreover, the nodes running out of power should be capable of requesting energy on urgent basis. Further research is also needed to assess the number of external power sources needed based on the fixed sensor density in a typical agricultural field and should also be able to accommodate mobile sensors.

Recently, magnetic near field inductive power transfer approach has been proposed for magnetic induction based wireless underground sensor networks [91]. There are many standards available for magnetic near field inductive power transfer. However, its range is limited to distances less than 1m.

Far field wireless power transfer (WPT) can be used for long energy transfer. There are many advantages of long-range wireless power transfer approach in the underground sensing and communications in digital agriculture.

- Physical contact with devices and wired connection can be completely removed
- Mobility can be achieved in energy transfer as an external power sources can charge many devices in the field
- On-demand and reliable delivery can be insured all conditions in contrast to other sources of power which are weather or farm activity dependent

A concurrent wireless and power wireless network can be effectively used to transmit data and power in full-duplex settings. First case is aboveground to underground energy transfer in which solar energy harvested from the aboveground nodes can be transferred to underground nodes. In the second case of underground to aboveground energy transfer, the energy harvested by the underground nodes from the vibration and bacterial sources acting as fuel cells can be transmitted to aboveground nodes. Therefore, both this bi-directional energy transfer will lead to more reliable and sustainable operation for longer periods of time anywhere and anytime.

3.10.3 Solar Power

Solar power transfer through aboveground nodes can also be used in the agriculture fields in the sun belt area to transfer power to underground nodes. The harvested solar energy can be steered to different underground nodes using the soil moisture adaptive beamforming with phased antenna arrays [154]. The Solar Power Radio Integrated Transmitter (SPRITZ) can be developed combined with solar cells that provide the DC power.

3.10.4 Energy Harvesting Challenges

The design underground energy transfer in digital agriculture should address following major issues:

- Transfer range for fully functional underground energy transfer network, underground-to-underground power transfer range should be 35m, which is the current communication range for the same wireless channel. However, for the transfer link where there are sources available aboveground the energy transfer range of 100m is desirable to cover a standard 300x300m agricultural field.
- Multipath Support. Energy transfer technique should be able to function where direct line of sight is not available. During plant growth in the growing season, many reflections from soil-air interface and multipath can exist which can pose critical challenges to effective energy transfer.
- Efficiency: Highly effective approaches are needed for through-the-soil power transfer. Because of complex permittivity of the soil high attenuation of wireless signals carrying data and power can reduce the efficiency of these approaches. High RF to DC conversion efficiency of devices is also vital for efficient energy harvesting.
- Mobility. Since multitude of farm machinery and pickup trucks can function in the field, hence, mobility power transfer will enhance the efficiency as compared to the fixed external power sources in the field.
- Accessibility: The under wirelesses power transfer approaches should be resistant to the changing crop pattern, weather, irrigation conditions. Ubiquitous accessibility will ensure reliable power supply in the wake of changing environmental conditions.
- Standards for in-field power should be developed so that all existing and new digital agricultural devices can be compatible and function in the transfer network.
- Energy consumption storage. There is also need of development of new methods to store energy at the underground nodes and reducing energy through development novel adaptive duty cycling approaches.

- Frequency spectrum. Types of uniform power and data transfer in digital agriculture should be used to effectively utilize the underground frequency spectrum (less than 1 GHz) within the bounds of existing delay spread and coherence bandwidth.

3.10.5 Combined Power and Data Transfer in Digital Agriculture

The different types of uniform power and data transfer in digital agriculture are discussed in the following:

- Concurrent transfer of data and power. The same channel is used for power and data transfer. The power sensor can be integrated in the receiver nodes (co-located) or two separate devices can be used this type of transfer.
- Uni-directional data and uni-directional power, one line is used for transfer of power (from transmitter to receiver) and other link is used for data (from receiver to transmitter)
- Time-shared approach, channel is shared between data and energy by using the time sharing approach depending on the need of the energy and information transfer

3.11 The Ag-IoT Systems

The academic and commercial IOUT systems are given in Tables 3.1 and 3.2, whereas their classification is shown in Fig. 3.8.

Table 3.1 The academic IOUT systems [202]

Architecture	Sensors	Comm. Tech.	Node density
Automated irrigation system [65]	DS1822 (temperature) VH400 (soil moisture)	OTA, ZigBee (ISM)	One node per indoor bed
Soil scout [192]	TMP122 (temperature) EC-5 (soil moisture)	UG, custom (ISM)	Eleven scouts on field and a control node
Remote sensing and irrigation sys. [90]	TMP107 (temperature) CS616 (soil moisture) CR10 data logger	OTA, bluetooth (ISM)	Five field sensing, one weather station

(continued)

Table 3.1 (continued)

Architecture	Sensors	Comm. Tech.	Node density
Autonomous precision agriculture [42]	Watermark 200SS-15 (soil moisture) data logger	UG, custom (ISM)	Up to 20 nodes per field
SoilNet [25]	ECHO TE (soil moisture) EC20 TE (soil conductivity)	OTA, ZigBee (ISM)	150 nodes covering 27 ha
MOLES [187]	Magnetic induction communications	Magnetic induction	Indoor testbed
Irrigation nodes in vineyards [200]	Yield NDVI	Variable rate irrigation	140 irrigation nodes per field
Sensor network for irrigation scheduling [38, 167]	Capacitance (soil moisture) watermark soil moisture sensors	OTA	6 nodes per acre
Cornell's digital agriculture [33]	E-Synch, touch-sensitive soft robots vineyard mapping technology, RTK	OTA	Field dependent
Plant water status network [139]	Crop water stress index (CWSI) modified water stress index (MCWSI)	OTA	Two management zone—two treatments in each zone
Real-time leaf temperature monitor system [98]	Leaf temperature ambient temperature relative humidity and incident solar radiation	OTA	Soil and plant water status monitors,
Thoreau [220]	Temperature, soil moisture electric conductivity and water potential,	OTA	Based on Sigfox,
FarmBeats [196]	Temperature, soil moisture Orthomosaic and pH,	OTA	Field size of 100 acres
Video-surveillance and data-monitoring WUSN [55]	Agriculture data monitoring Motion detection, Camera sensor	OTA	In the order of several kilometers
Purdue university's digital agriculture initiative [134]	Adaptive weather tower PhenoRover sensor vehicle	OTA	Field dependent
Pervasive wireless sensor network [210]	Soil moisture, camera	OTA	Field dependent
Pilot sensor network [96]	Sensirion SHT75	OTA	100 nodes in a field
SoilBED [46]	Contamination detection	UG	Cross-well radar

Table 3.2 The commercial IOUT systems [202]

Architecture	Sensors	Comm. tech.	Node density
IRROmesh [84]	200TS (temperature)	OTA, custom (ISM)	Up to 20 nodes network mesh
	Watermark 200SS-15 (soil moisture)	OTA, cellular	
Field connect [88]	Leaf wetness	OTA, proprietary	Up to eight nodes per gateway
	Temperature probe	OTA, cellular	
	Pyranometer	OTA, satellite	
	Rain gauge		
	Weather station		
SapIP wireless mesh network [43]	Plant water use	OTA	Up to 25 SapIP nodes with 2 sap flow sensors each
	Measure plant stress		
	Soil moisture profile		
	Weather and ET		
Automated irrigation advisor [195]	Tule actual ET sensor	OTA	Field dependent
Internet of agriculture-biosense [24]	Machinery auto-steering and automation	OTA	Field dependent—Real-time irrigation decision making
	EC probe & XRF scanner		
	Electrical conductivity map		
	NDVI map		
	Yield map		
	Remote sensing		
	Nano and micro-electronic sensors		
	Big data, and Internet of Things		
EZ-farm [77]	Water usage	OTA	IBM bluemix and IBM IoT foundation
	Big data, and Internet of Things		
	Terrain, soil, weather		
	Genetics		
	Satellite info		
	Sales		

(continued)

Table 3.2 (continued)

Architecture	Sensors	Comm. tech.	Node density
Internet of food and farm (IoF2020) [82]	Soil moisture	OTA	Field dependent
	Soil temperature		
	Electrical conductivity and leaf wetness		
Cropx soil monitoring system [34]	Soil moisture	OTA	Filed dependant
	Soil temperature and EC		
Plug & sense smart agriculture [128]	Temperature and humidity sensing	OTA	Field dependent
	Rainfall, wind speed and direction		
	Atmospheric pressure		
	Soil water content, and leaf wetness		
Grain monitor-temputech [191]	Grain temperature and humidity	OTA	Multiple depths in grain elevator
365FarmNet [1]	Mobile device visualization tool for IOUT data	OTA	Field dependent
SeNet [166]	Sensing and control architecture	OTA	Field dependent
PrecisionHawk [130]	Drones for sensing	OTA	Field dependent
	Field map generation		
HereLab [69]	Soil moisture	OTA	Field dependent
	Drip line PSI and rain		
IntelliFarms [80]	YieldFax	OTA	Field dependent
	Biological		
	BinManager		
IoT sensor platform [83]	IoT/M2M sensors	OTA	Field dependent
Symphony link [185]	Long range communications	OTA	Field dependent

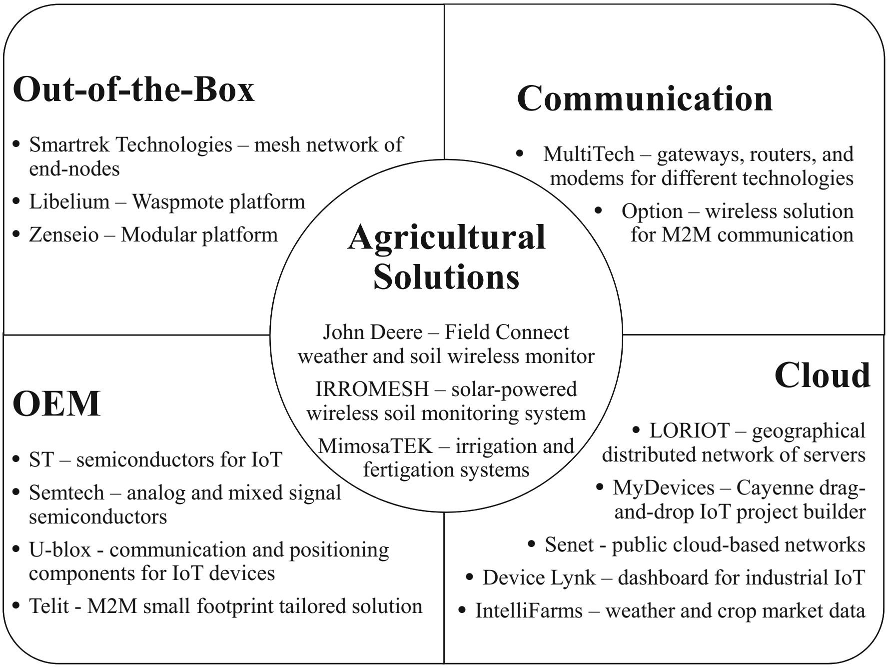

Fig. 3.8 The classification of commercial IOUT solutions [202]

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Chapter 4
Internet of Things for Water Sustainability

Abstract The water is a finite resource. The issue of sustainable withdrawal of freshwater is a vital concern being faced by the community. There is a strong connection between the energy, food, and water which is referred to as water-food-energy nexus. The agriculture industry and municipalities are struggling to meet the demand of water supply. This situation is particularly exacerbated in the developing countries. The projected increase in world population requires more fresh water resources. New technologies are being developed to reduce water usage in the field of agriculture (e.g., sensor guided autonomous irrigation management systems). Agricultural water withdrawal is also impacting ground and surface water resources. Although the importance of reduction in water usage cannot be overemphasized, major efforts for sustainable water are directed towards the novel technology development for cleaning and recycling. Moreover, currently, energy technologies require abundant water for energy production. Therefore, energy sustainability is inextricably linked to water sustainability. The water sustainability IoT has a strong potential to solve many challenges in water-food-energy nexus. In this chapter, the architecture of IoT for water sustainability is presented. An in-depth coverage of sensing and communication technologies and water systems is also provided.

4.1 Introduction

When the well runs dry we know the worth of water.—Benjamin Franklin

The survival of the humanity is contingent upon the availability of water. The aquatic ecosystems that include groundwater, oceans, river, lakes, streams, and estuaries supply a wide range of resources and services to the community [18, 56]. These are important for water storage, regulation of water quality and quantity, food provision, recreation, and transport of water and substances to downstream [14, 92]. The droughts and flooding impacts the normal functionality and is a main cause of reduction in its tolerance and diversity, a vital factor for sustainable community [63, 126, 131]. The contents of the chapter are shown in Fig. 4.1.

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Fig. 4.1 The internet of things for sustainable water

The water, energy, and land-based systems are linked in many different ways[39, 63, 107]. The precipitation patterns are changing rapidly due to the ocean and atmosphere warming [14, 17, 31, 33, 43, 101]. The most visible effects of these phenomena include increase in the duration of dry periods, higher evaporation, and rapid snow melt [46]. These cascading effects propagate to the water cycle, which encompasses complete and dynamic processes of water movement and circulation in the Earth system. Due to global warming effects, these water cycle processes (see Fig. 4.2) are exhibiting unpredictable increase and decrease with abundant (flooding) or little to no water availability (drought) [33]. The decrease in the amount of available water is a major threat to entire ecosystem. Similarly, flooding poses a major risk to communities and infrastructure.

Significant changes are also being observed in streamflow patterns with peak flows moving to the beginning of the year [111, 133]. The increase in amount of rain as compared to the snow is also impacting water storage facilities. The rate of evapotranspiration is a major element of the water cycle, which represents the evaporation of water from different sources such as oceans, lakes, plants, soils, and rivers [93]. Its rate is impacted by wind, solar radiation, humidity, and wind. Consequently, water content of soil, water runoff, and groundwater recharge are impacted by these variations in rate of evapotranspiration [33, 78]. Among these factors, the soil water content is significant because of its implications in agriculture and air evaporation and temperature. This increase in evaporation is considered to be a big factor contributing to increases in dry periods and shorter droughts on seasonal basis [42]. These changes in precipitation patterns are also impacting the municipal water supplies [103]. For a reliable water supply to cities, the utility management companies are facing many challenges in water storage

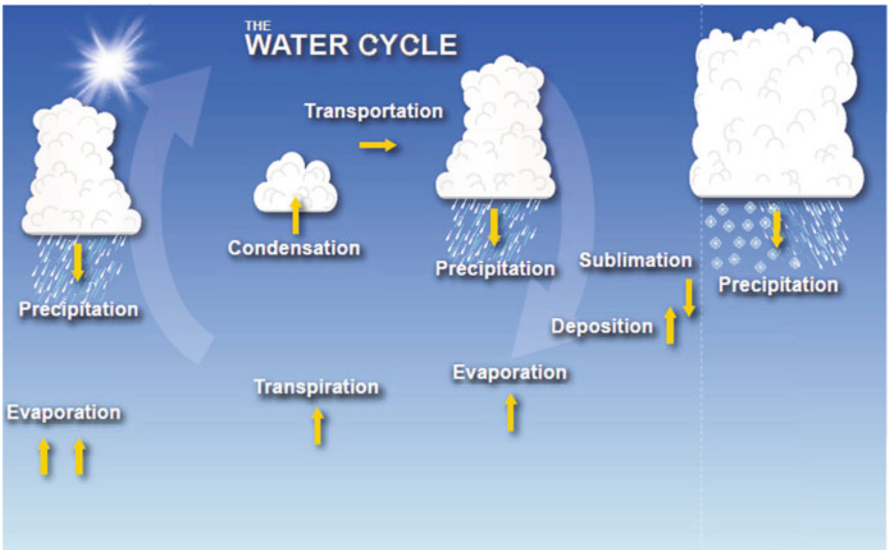

Fig. 4.2 The water cycle

due to projected decline in supply and increasing population. World population is expected to reach 9.8 billion people by 2050, with corresponding increase of a 25 to 70% in food production [129]. The world food production challenges span beyond UN agenda of eradicating malnutrition and poverty by 2030. According to WHO, daily minimal human demand of water is 1.84 gallons per day, whereas the recommended water need to maintain adequate hygienic is 5.28 gallons [109]. For a total human population of 7.7 billion, the global water need of freshwater is 40.65 billion gallons. UN sustainable development goal (SDG 6) is about providing safe water [110].

The crop and landscape irrigation also depends on the water, being the largest withdrawal of water. Although 3/4 of our planet is covered with water, only 2.5% constitutes the freshwater. Approximately 70% of the available freshwater is frozen in glaziers and the ice caps. The residual 0.75% of freshwater is in swamps, subsurface, lake and river, living organisms, and the atmosphere. The 70% of the remaining 0.75% of freshwater is utilized in irrigation.

Water quality is another major challenge. The high streamflow takes sediments and pollutants to the water. Whereas, the well below-average rates of streamflow also result in decrease of water quality. Similarly, heavy precipitation, increased intensity and scale of wildfires, impacts fertilizer usage contributes nutrients, contaminants, and sediments from the surface water to downstream [35].

The freshwater aquifers and wetlands are also vital for the water sustainability. These are being undermined by many factors including changing sea levels, surface and groundwater usage, and storm surges [16]. The saltwater gets mixed with underground and surface water due to rise in sea levels. The saltwater also flows

upstream to make up the deficiency in river flows that is caused by high withdrawals. Moreover, storm surge and rise in sea levels also impact the urban underground infrastructures such as storm drainage and sewer treatment.

In water-energy nexus, the demand of water for energy production is increasing rapidly. Water is needed in hydro-electric dams for turbine, in thermo-electric power plant for steam, and cooling of the equipment in nuclear power generation to absorb heat. Likewise, the energy is needed to draw out water from rivers and aquifers, to transport it to storage and treatment facilities, to distribute water supply, and finally, to collect waste water. Collectively, energy and water need land resources.

4.2 Water Sustainability IoT

The water sustainability IoT contain components such as water things, sensing, water quality measurements, cleaning and treatment technologies, and water resource management. The elements of the water IoT are shown below:

- Groundwater, fresh water, and surface water
- Precipitation, river flow, lakes, and wetlands
- Evapotranspiration, hydrology, and hydraulics
- Aquifer and runoff
- Irrigation, recycling, and cleaning

4.3 IoT as an Enabler for Sustainable Water

In this section, the IoT paradigm is discussed as an enabler of sustainable water.

4.3.1 Advantages of Sustainable Water IoT

The water IoT is envisioned to provide accurate decision support systems to guide technological and societal progress in water use. It enables annual precipitation monitoring and river-flow variation observations. Accordingly, very heavy precipitation, dry periods, and seasonal and short- and long-term droughts can be predicted at spatial and temporal scale. Moreover, based on the IoT sensing technologies for withdrawal of groundwater, and aquifer recharge, the availability of demand can be ascertained. The surface and groundwater supplies are decreasing because of the consumption, withdrawal, precipitation, runoff, combined with changes in consumption and withdrawal. The determination of variations in surface water and groundwater usage patterns will help to attain substantial freshwater aquifers and wetlands. The total precipitation measurements can be used to forecast potential

flooding threats. Therefore, risks to economy, community infrastructure, human health and property, and human safety can be reduced.

The state-of-the-art IoT technology, ecological standards, and indicators are useful in achieving sustainability goals. There are many advantages of the water IoT for sustainable community development. The cumulative water withdrawals scale and impact can be modeled on ecosystem through IoT data collection tools. The development of novel sensing technologies enables monitoring of water IoT such as wetlands and lake inflows. Accordingly, based on the sensing of water IoT, better approaches can be developed for water sustainability indicators which will contribute to the aquatic and terrestrial ecosystem resilience. Other important enabling sensing includes water and air temperatures, runoff, and precipitation.

Using the integrated water IoT paradigm, the connection between ecological parameters and hydrology flow regime and groundwater can be better understood through the identification of impact of flow regime thresholds. One example is flow variations link to invasive species. The water quality can be improved by reduction of pollutants caused by human activities. The IoT paradigm can also inform deployment of new systems for reduce water use. Moreover, the water cleaning and recycling technologies can be developed and integrated into the system through sensing of the water pollutants, nitrogen, and sediments. Accordingly, lake and water quality can be improved. Moreover, critical data sets (e.g., data related to stream and river flow, groundwater, waterborne disease, water usage, and paleoclimate reconstruction) can enable advance research and better understand of the echosystem (Fig. 4.3).

4.3.2 Research Challenges Needs in Sustainable Water IoT

In this section, the research needs in support of all aspects of the sustainable water ecosystem are discussed.

- The better insights are needed in relationship between groundwater and surface water through improvements in water IoT monitoring tools and infrastructures [34, 48].
- In the ecology domain, a particular emphasis is needed on sensing of ecological parameters and lakes, wetlands inflows. The connection between point and non-point sources against freshwater supply also needs more investigation [45].
- In urban localities, more advanced real-time pathogens, contaminants and chemical compound sensing technologies are needed. Novel techniques are needed for nutrient reduction, detection of new type of contaminants, spill detection, source tracking [60].
- There is need of whole cycle measurements integration into sustainable water IoT with emphasis on communication networks to eliminate dependency on detached measurements to assess the effects of climate change, land use, water conservation activities including water source and discharge [44].

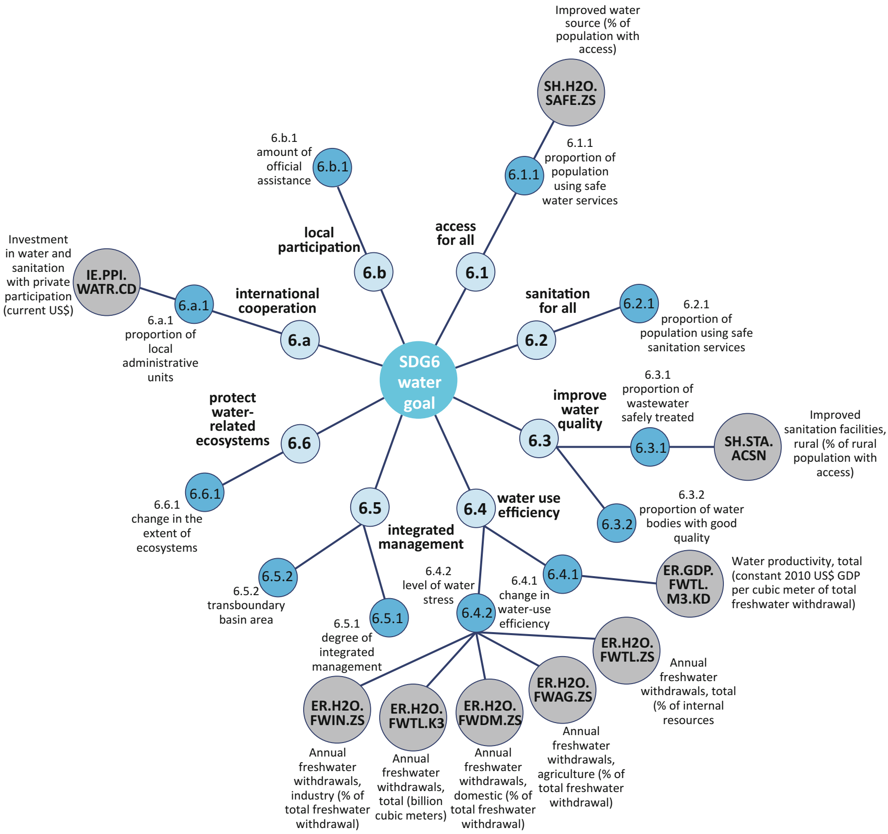

Fig. 4.3 The sustainable development goals related to water sustainability

- Other important technology needs for sustainable water integration are in the area of inexpensive storage and metal removal [22, 127].

4.4 Water Sustainability IoT Monitoring and Applications

The water quality is indicator of the state of biological, chemical, and physical properties of water [115, 123]. The importance of the water quality for sustainable environment and ecosystem cannot be overemphasized [130]. The water quality measurements in river and lakes and other water bodies are important to identify inadequate oxygen supply caused by extra amounts of nutrients and algal blooms. Through monitoring the impact of the climate change, human activities can be better understood [57]. Accordingly, it enables better decision and policy making. Moreover, the impact of the sediment loading can also be analyzed by using the

turbidity measurement. The monitoring can be done by using different approaches such as sampling, continual monitoring, and remote sensing are all used to collect water quality data in estuarine and coastal ecosystems, surface and ground water, stormwater, and ballast water [57]. In this regard, novel pathogens, nutrients, and chemical contaminants sensing technology are needed.

Similarly, the water monitoring in urban areas includes:

- Accession and transport of rainfall and runoff data for sewage and stormwater networks [105]
- Management of stormwater retention base [122]
- Water supply infrastructure monitoring [95]
- Pipeline system to identify issues related to water supply shortage [54]
- Industrial activities impacted water quality monitoring [69]

For sustainable water IoT, development of novel monitoring technologies for the entire water cycle is needed. The sustainable water IoT is envisaged as to integrate different type measurements at large scale. This paradigm removes the issue of single point failures and insufficient data for decision making. It also gives insights into the baseline conditions at different spatial and temporal scales (including natural perturbations and industrial impacts). Accordingly, various relevant baseline indicators can be utilized for policy making and remedial actions by providing accurate and certain data. The sustainable water IoT enables development and integration of different types of systems for robust evaluation of water ecosystems. The predictive models can be developed and integrated into the paradigm for different water use scenarios (e.g., drinking water, discharge, and industrial use).

4.4.1 Applications

The important water monitoring applications are discussed below:

- Potable water monitoring. For chemical properties including pH, nitrates, and dissolved oxygen (DO).
- Chemical leakage monitoring. The extreme pH and low dissolved oxygen levels are used to identify spills because of sewage treatment plant or other pipeline issues in rivers.
- Pollution levels monitoring: Temperature, pH, salinity, nitrates dissolved oxygen monitoring in seawater.
- Corrosion and limescale deposit monitoring: The pH, conductivity, Calcium ($Ca+$) temperature, and magnesium ($Mg2+$) concentrations monitoring.
- Aquatic life conditions monitoring. Water conditions of aquatic animals such as fish.
- Swimming pool monitoring: The pH, oxidation-reduction potential (ORP), and chloride values to assess water quality in swimming pools.

4.4.2 Source Water Monitoring

Source water is impacted by different factors including seasonal weather changes, and upstream discharge. The source water quality monitoring enables selection of proper treatment options. Groundwater has low content of natural organic matter (NOM) and therefore can be disinfected by using chlorine disinfection techniques.

4.4.2.1 Surface Water

Surface water comes from rivers, lakes, and other reservoirs. It is the vital source of water production. The groundwater has high content of natural organic matter (NOM) and needs proper disinfection techniques.

The important water monitoring parameters are discussed below:

- Ammonia. The ammonia level can change remarkably in all seasons and requires consistent monitoring. Ammonia reaction chlorine disinfection leads to formation of chloramines which produce different issues [51].
- Free Chlorine: The free chlorine is mixed to the groundwater for ammonia transformation to chloramines, which breaks by further chlorine, hence making free chlorine as leftover disinfectant. The free chlorine monitoring is done to achieve desired levels. It is also used to eliminate amalgamation of manganese and iron and manganese for subsequent removal through filtration [85].
- pH. The pH is used for chlorine disinfection process optimization. It indicates the acidity and alkalinity of water [25].
- Total organic carbon. The TOC is measure of the carbon present in organic compounds of the water. It guides selection of proper treatment method through byproduct precursor's removal [79].
- UV254. The UV254 gets its name from its wavelength of 254nm. It is used to measure organic matter (OM) in water. The OM reacts to chlorine to form disinfection byproducts (DBPs). Different events impact the OM in the water such as storm, increase in nutrients from human activities [128].
- Turbidity. The turbidity is the indicator of water transparency loss caused by the suspended particulates. The large turbidity levels negatively impact the disinfection process by preventing the ultraviolet disinfection. Turbidity variations also indicate weather events such as rain and floods [96].

4.5 Sensing in Sustainable Water IoT

The real-time sensing is a vital component of the sustainable water IoT. The monitoring applications enabled through this sensing mechanism are being adopted by industry. It also enables improved efficiency water treatment and recycling operation. A detailed overview of water sensing technologies is given in next section.

4.5.1 pH Sensing

A common measurement of the water is pH, which is equivalent to negative of the logarithm of hydrogen-ion concentration in water. It is used to measure acid and alkaline properties of water on a scale of 0–14, where 7 is considered as neutral. The pH value higher than 7 denotes alkalinity, whereas the values less than 7 indicate acidity. An increase or decrease of 1 in acidity or alkalinity represents ten times change. Different types of the pH sensors are explained below:

4.5.1.1 Combination (Electrochemical) pH Sensor

The combination(electrochemical) sensor is a widely used method to sense pH values [10]. It consists of a reference and measuring electrodes. Where the actual detection of the pH variations is done based on the measurement electrode and reference electrode provides a steady signal for comparison purpose. An impedance based metering instrument is used for pH value visualization which converts millivolt signal to pH values.

4.5.1.2 Three-Electrode pH Sensor

Three-electrode pH sensor also referred to as differential pH use three electrodes for pH measurements [55]. Where the differential detection of the pH variations is done based on the measurement of two electrodes and reference metal ground electrode provides a steady signal for comparison purpose. Three-electrode pH sensor is less error-prone in terms of reference signal.

4.5.1.3 Laboratory pH Sensor

The laboratory pH sensor is a type of electrochemical pH installed in 1.2 cm glass/plastic unit. This type of sensor is used in laboratory for learning and discovery purpose. This is also used in environmental monitoring and pool sampling and can be easily tailored to match desired application requirements [82].

4.5.1.4 Single-Chip pH Sensors

The single-chip pH sensors are used for pipeline and underground tank monitoring. It is designed to provide continuous monitoring of the pH values. Its robust design can sustain harsh environment with capability to work for longer duration for duration without interruption [41].

4.5.2 *Conductivity Sensing*

The electrical conductivity, reciprocal of resistivity, is the measure of the capability of a solution or medium's electric conductance [80]. Without the presence of ions, the water is not a high conducting medium. Therefore, conductivity measure indicates the amount of ion present in water. The electrical conductivity measurements can be presented in different units (e.g., ion concentration TDS, and salinity). It is expressed in micro-Siemens per centimeter, $\mu S/cm$, micro-Siemen. For higher conductivity values are also expressed in milli-Siemens. There are several different conductivity measurement units in use today.

4.5.2.1 Conductivity Measurement Units

Conductivity measurements are often converted into TDS units, salinity units, or concentrations. These units of measurements are explained in the following:

- Total dissolved solids. TDS is the indirect measure of number of ion amount, measures through electrical conductivity, that is indicated as parts per million (ppm) or mg/l [94]. In environment, where highly dissolved ionic solids are present, the TDS measurements produce accurate results. The TDS is also being used in water treatment industry.
- Salinity. It is also an indirect measure which is usually expressed as ppt. Both TDS and salinity measurements are sensitive to temperature, ion types, and concentration. Accordingly, one unit can be converted to another [84].
- Concentration. Based on the knowledge of the composition of the ions, the concentration can be ascertained from the conductivity [8].

4.5.2.2 Conductivity Sensors

The electrical conductivity sensors are based on inductive, 2-electrode, 4-electrode based methods. These electrical conductivity measurements from these sensors can be changed to salinity, total dissolved solids, and concentration. Different types of conductivity sensors are discussed in the following:

Contact-Based Conductivity Sensors The contacting conductivity sensors are used to conductivity by making a physical contact, from two sides, to the understudy material [90]. These sensor sides are made by using different materials such as platinum, graphite, steel. An alternate current (AC) waveform is applied and transmitted through once, which then propagates through sample being sensed. Accordingly, the signal is received at the other side where its intensity is used to measure the conductivity in TDS, or micro/milli-Siemens.

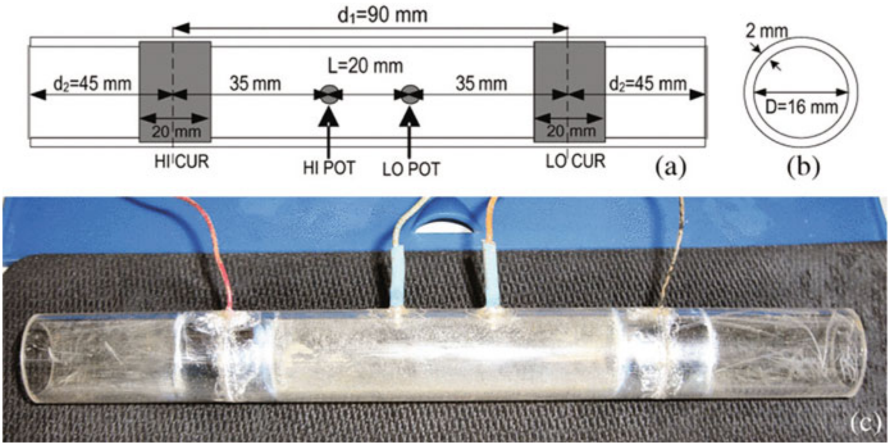

Fig. 4.4 A four-electrode conductivity sensor and an integrated temperature sensor unit. (**a**) Longitudinal sectional-view geometry. (**b**) Transversal sectional-view geometry. (**c**) Actual sensing unit [90]

Inductive Conductivity Sensors The inductive conductivity sensors, also called the toroidal conductivity sensors, work on the principal of magnetic induction by use a two coil (antenna) induction system in plastic assembly. The transmitter antenna induces a magnetic field that produces an electrical current on the understudy sample. The receiver antenna measures the magnetic field, where the corresponding current intensity indicates the ion concentration. Due to its ability to remove polarizing effects and fouling resistant, the inductive sensor produces high quality measurements as compared to the contact-based conductivity sensor. The toroidal sensors are being used in sea water monitoring. A four-electrode conductivity sensor and an integrated temperature sensor unit are shown in Fig. 4.4.

Conductivity in Water Treatment Based on the application need, various levels of conductivity values are used to assess the purity of the water (e.g., drinking water generally has the conductivity value of around 1 milli-Siemens per centimeter, highly pure water has the conductivity values are less than 1 micro-Siemens per second).

The conductivity levels of the different liquids are given in Table 4.1 [100].

4.5.3 *Dissolved Oxygen Sensing*

The oxygen dissolved per unit of water is called dissolved oxygen (DO) [83]. Water gets oxygen through different ways:

- The aeration also known as movement by turbulence
- Through diffusion in surrounding air

Table 4.1 The conductivity levels of the different liquids

Liquid type	Conductivity level
Fresh water	0–1 mS/cm
Ultra-pure water	0.00005 mS/cm
De-ionized water	0.00005–0.001 mS/cm
Reverse osmosis water	0.00005–0.2 mS/cm
Drinking water	0.20–0.80 mS/cm
Slightly salty water	1–45 mS/cm
Sea water	45–73 mS/cm
Highly salted water	72+ mS/cm

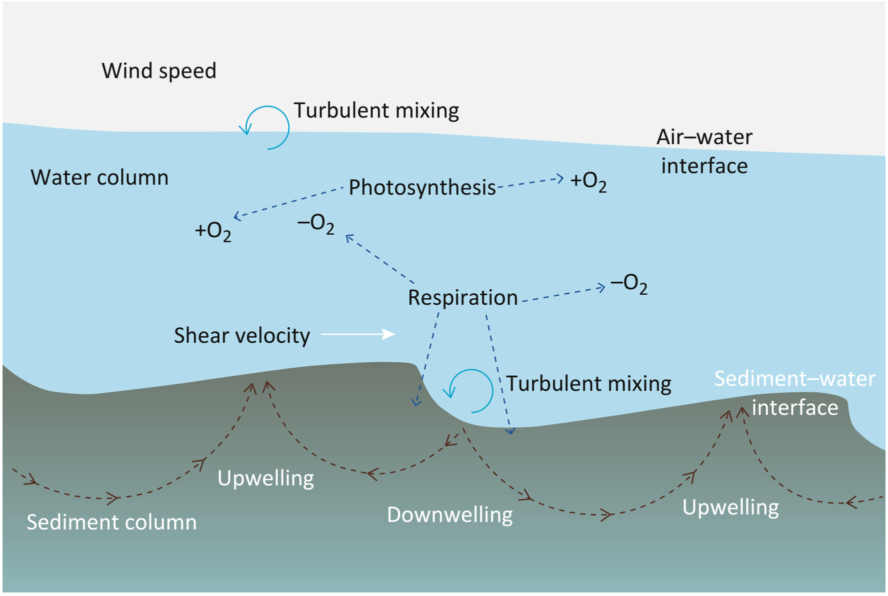

Fig. 4.5 A schematic side view showing major processes controlling stream and benthic dissolved oxygen concentrations [9]

- Aquatic plants
- Plant waste by photosynthesis in water column
- Atmosphere

Still water sources (e.g., lakes) have low oxygen as compared to the running water source such as streams and rivers. A schematic side view showing major processes controlling stream and benthic dissolved oxygen concentrations is shown in Fig. 4.5. The DO is a vital indicator of the quality of the water and aquatic life as oxygen is must for breathing. Different types of DO sensors are explained in the following.

4.5.3.1 Galvanic DO Sensor

The galvanic DO sensors use a cathode and anode with an oxygen permeable membrane to separate these two from the sample understudy water [9, 37]. The purpose of the permeable membrane is to permit oxygen contained in the sample to be diffused in the instrument, accordingly, the cathode reduces it there. Due to this chemical reaction, an electronic signal is generated that propagates from cathode to anode, and subsequently into the sensor, where the difference in pressure is measured that changes according to the samples oxygen's pressure. Because the diffusion rate and partial pressure increase with oxygen concentration, there is a proportional increase to the current.

4.5.3.2 Optical Dissolved Oxygen Sensors

A die is used in the optical dissolved oxygen sensor [66] to sense wavelength of the light. Then a paint layer of oxygen is placed on the dye which molecules interact with iluminescence. It acts as a filter for other compounds. The color of the die changes to glowing red when it is exposed to the light. The sensor measures luminescence from the emitted light by using the photo-diode, which is compared to reference value to ascertain oxygen dissolved in water.

4.5.4 Eutrophication and Nutrient Sensing

Eutrophication is unrestrained intake and enrichment of nutrients (e.g., nitrogen and phosphorus) which mostly come from anthropogenic sources (e.g., human activities) [53, 116]. This issue is being observed in reservoirs, rivers, estuaries, lakes, and other coastal regions. The presence of high nutrients concentrations leads to production of toxins, hypoxia, fish kills, and harmful algal blooms (HABx) that are harmful to aquatic life and humanity [11, 13, 36, 71]. These nutrients are carried along with agricultural runoff, domestic yard fertilizers and detergents, fossil fuels combustion caused atmospheric deposition, stormwater, wastewater. Due to infeasibility of mitigation, preventing that high intake in lakes, rivers, and oceans through nutrient sensing and in situ measurements is a viable option to avoid potential problems to the ecosystem. Accordingly, compliance limits for nutrient discharges can be established. The nutrient sensing also enables other policy level decisions such as flow rate and treatment options at water bodies. It also provides insights into the relationship of geochemical, hydrological, and biological processes. With the increasing severity and intensity of HABs, there is a need of in situ nutrient sensors for nitrate, ammonium, nitrite, ammonia, total phosphorus, total nitrogen and soluble reactive phosphorus with strong emphasis on the nitrate and nitrite sensors. The nutrients sensing technologies are discussed in the following:

4.5.4.1 Optical Nutrient Sensor

It works by using advanced spectral absorption (UV) [113] through a photometer and provides accurate and high resolution, and chemical-free fast response time. However, it is expensive and only senses nitrate. Moreover, the energy consumption of the sensor is high. It can operate in harsh environments such as blue-ocean nitraclines, storm runoff in lakes and rivers, and streams [72].

4.5.4.2 Wet-Chemical Sensor

It operates on the principal of wet-chemical calorimetric reaction with sensing through photometry [6]. It also provides accurate high resolution measurements of phosphate, ammonium, and nitrate. It is suitable for point and non-point source nutrient measurements in different environments (e.g., lakes, reservoirs, rivers, streams, rivers, canals, and channels, estuaries, and oceans) It supports real-time measurement of dissolved phosphate.

4.5.4.3 Ion-Selective Electrodes Sensor

It operates on direct potentiometry between a reference electrode and a detecting electrode [24]. It can sense ammonium and nitrate. However, it has low resolution as compared to the wet-chemical sensors and optical sensor. The accuracy of this sensor is also sensitive to the ionic interference.

4.5.5 Water Flow Sensors

The water flow and discharge measurements are important to ascertain the water amount flowing through a channel. These sensors are also used to predict flooding. In flow rate measurements, different inferential approaches such has change in water velocity and kinetic energy are employed. The different types of water flow sensors are explained in the following [50]:

- Rota-meter. A rotameter is used for volumetric flow rate measurement of fluids in a closed tube. It works by allowing flow to the cross-sectional where the travel of the flow changes and accordingly can be measured [59].
- Magnetic-flow meter. A magnetic flow meter is a flow measurement instrument that works on the voltage induction principal. It measures the flow by using a magnetic field which causes difference in potential corresponding to the velocity of flow normal to flux lines [52].
- Turbine flow meter. A turbine flow meter is used to sense the volume of the flow by using the rotation of the blades caused by the movement of flow. By measuring

the rotor velocity which is directly proportional to the fluid velocity, it provides accurate measurements [3].
- Venturi-tube flow meter. Venturi meter is used to measure flow by using a pipe's converging section to induce an increase in velocity of low, which leads to a proportional drop in pressure that is used to deduce flow rate can be deduced. The water supply industry uses Venturi-tube flow meter for flow measurements [62].

4.5.6 Temperature Sensing

A temperature sensor, as the name indicates water temperature measurement instrument [114]. The different types of temperature sensors are explained in the following:

- Thermocouple. A thermocouple uses two different types of electrical conductors which are used to form junctions at two different temperatures [67]. A thermocouple generates a voltage that depends on the temperature (thermo-electric effect). Accordingly, the voltage interpretation provides temperature value.
- Resistance Temperature Detector. A RTD determines temperature by using the electrical resistance of the sample under study which changes with the change in temperature [5].
- Thermistor. The electrical resistance of the thermistor changes with temperature and accordingly is used to measure temperature [120].

4.5.7 Satellite Sensing

The water remote sensing is used for recording the water color spectrum (color of water body) and is based on optics and water's apparent optical property [19, 47]. It is used to sense presence of different natural components of the water. When the light field is applied to water, the angular distribution of the field impacts the water color depending on the type and amount of water substances. Therefore, the concentrations of optically active substances are determined with this distribution changes [30].

The reflectance of the light from the water surface is measured using different types of optical measurement device such as radiometers, and spectrometers mounted on air- and space-born devices. The water quality is studied from different parameters such as chlorophyll-a and suspended particulate matter concentration, where high amount of detected concentrations of these parameters show eutrophication-caused algal bloom (HAB).

The Ocean Color Radiometry Virtual Constellation (OCR-VC) is a system to produce data sets by using ocean color radiometry satellites to assess the climate change impacts [38].

The various ocean color radiometry networks are listed in the following:

- International Network for Sensor Inter-comparison and Uncertainty Assessment for Ocean Color Radiometry (INSITU-OCR). The purpose is to integrate and visualize different remote sensing tools for satellite sensor inter-comparisons and uncertainty assessment for remote sensing products
- Ocean Color Essential Climate Variables (ECV) [97]
- Global Climate Observing System (GCOS) [20]
- International Ocean Color Coordinating Group (IOCCG) [136]

4.6 Sustainable Water IoT Technologies and Systems

In this section, the sustainable water IoT technologies and systems are discussed.

4.6.1 Water Pollution Control

The discharge of toxic substances due to human activities (e.g., herbicides, domestic wastes, and insecticides) is one of the main factors contributing to the water pollution [68, 91]. Various types of compounds and chemicals are being detected in water sources indicating the severity of this issue. The other water pollutants come from livestock farms, waste from food processing plants, metals and chemical waste. Due to various types of water pollutants, a range of diverse techniques and methods are being used in water treatment. An architecture of a low-cost sensor network for real-time monitoring and contamination detection in drinking water distribution systems is shown in Fig. 4.6. The surface water and groundwater are two types of drinking water which generally require treatment for following types of contaminants [70, 132]:

- Biological contaminants (e.g., disease-causing bacterium, protozoa phylum, viruses, and parasitic worms [2]
- Inorganic chemicals (e.g., nitrogen species, metals, oxyanions, and radioactive nuclide) [134]
- Organic chemicals (e.g., natural organic matter (NOM) and faux organic chemicals from agro-industrial products) [7]

The major water treatment technologies are [15]:

- Coagulation. The solids are separated through the sedimentation process. It is then followed by the filtration process because the slowly settling tiny particles are hard to remove through the settling. Therefore, coagulation (grouping) is done through chemicals (e.g., alum) to form large particle groups.
- Membrane process. This treatment method is used filter out undesired pollutants from water. A membrane also acts like a filter with a capability to block certain

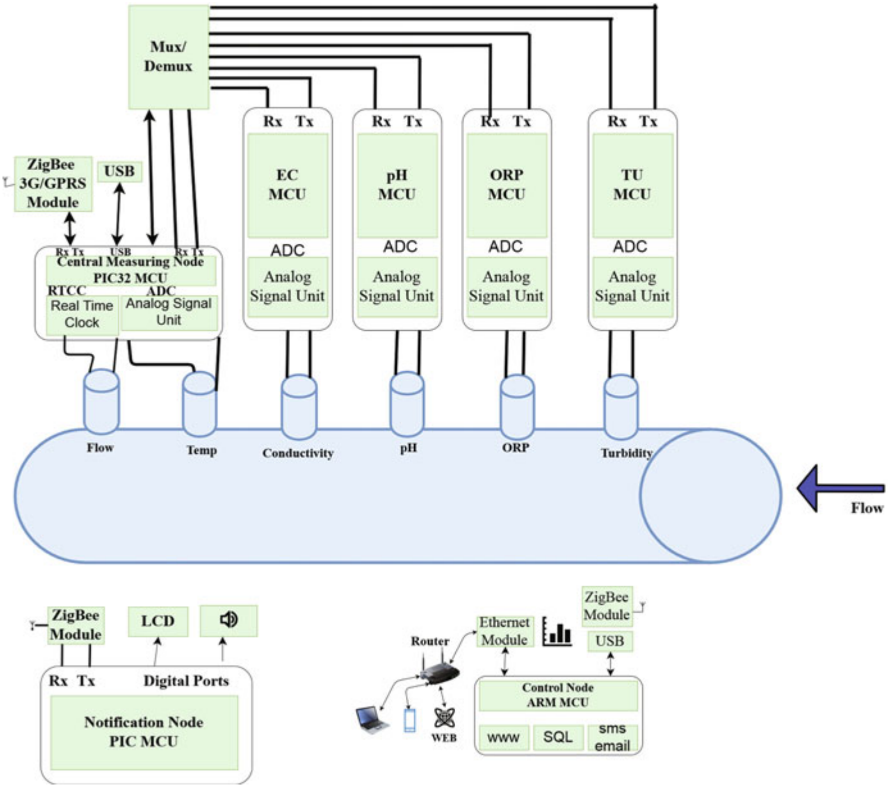

Fig. 4.6 An architecture of a low-cost sensor network for real-time monitoring and contamination detection in drinking water distribution systems [58]

constituents. It is employed in ground and surface water to obtain water for drinking, and to wastewater for industry needs.

- Adsorption and Biosorption. Adsorption refers to surface accumulation different components. It is a gas– or liquid–solid phenomenon. The biosorption process includes ion exchange (arsenic removal), complexation (complex association), surface precipitation, chelating (bonding), and coordination.
- Dialysis. The dialysis water treatment process is used to remove microbial and chemical compounds in two steps: (1) pre-treatment, where compounds are eliminated from the source water to get an early stage clean water, and (2) de-activating the leftover chemical and microbial compounds.
- Foam flotation. In dissolved air flotation (DAF) is a waste water treatment process oil and solids are removed. In this process, the high pressure air is dissolved in the water. Then, at atmospheric pressure, it is released in through flotation. The bubbles carry suspended matter adhered to them which is subsequently removed through skimming.

- Reverse Osmosis. Reverse osmosis (RO) uses the membrane process to filter dissolved compounds and suspended particles from water. Activated carbon (AC) filtration is also used to filter pesticides, chlorine, and organic solvents which are not filtered by RO. The sediment filtration removed silt particles.
- Photo catalytic degradation. It is used for reduction and oxidation of metals, photo catalytic reduction of oxyanion contaminants (e.g., NO_3^-, ClO_4^-), and destruction of per/polyfluoroalkyl substances (PFAS). The semiconducting material is also employed as heterogeneous photocatalyst.
- Biological and Bio-analytical methods. This process is based on the filtration of oxygenated water via different types of granular solids such as sand, coal, and granular activated carbon (GAC).

4.6.2 Ocean Acidification and CO_2 *Mitigation*

Ocean acidification (OA) is the process in which the acidity of ocean increases (decrease in pH value below 7) [40]. The UN Conference on Sustainable Development has declared OA as a major challenge to economically and ecologically ecosystem sustainability. The main cause of the ocean acidification is increase in CO_2 concentration from higher emissions which leads to chemical changes in sea water. Local and coastal pollution is also attributed to the ocean acidification. This process is harmful for the marine habitats in the ocean ecosystem. The following two methods are used for OA sensing [28]:

- OA Observing Vessels. In this approach, the sampling is done using research ships to sense variations in seawater carbon related chemical properties. The pH is the main parameter being measures using pH sensors. Moreover, by using this approach ocean acidification mitigation methods can be deployed at a large scales [21].
- Buoys and Autonomous Systems. For continuous and autonomous carbon measurements, the buoys are being used for high frequency measurements to get insights into variability in ocean acidification over diurnal, monthly, and yearly scale. These can be used to measure pH, bio-geo-chemical, and CO_2 in coral reef waters, sea, and coastal areas [99].
- Hydrographic Cruises. This approach is used to obtain for physical, chemical, and biological measurements of full vertical column base in harsh sea environments [23]

Although, OA can be mitigated through by limiting the emissions of atmospheric CO_2 levels, other options include restoration of wetlands, planting new forests and reforestation to increase absorption of atmospheric CO_2 levels, and by adding alkaline minerals to seawaters. Through IoT based decision support system following developments can also help in OA mitigation:

- Sensing of runoff and pollutants from fertilizers
- Digital fisheries management approaches
- Monitoring and protection of sediment loading and development of application of marine spatial monitoring
- Monitoring of local emissions sulfur dioxide and nitrous oxide emissions from coal plants

4.7 The Sustainable Water Case Studies

The case studies are discussed in the following:

4.7.1 Open Water Web

The open water data is an initiative of Advisory Committee on Water Information to integrate scattered water information into an open data web by leveraging prevailing infrastructure, systems for the purpose of development of novel water solutions and models, and for data sharing purpose [4]. The different components of the open data web are shown in Fig. 4.7. The three different use cases of open water web are given below:

- The National Flood Interoperability Experiment (NFIE). The purpose of this experiment to develop next-generation of flood hydrology tools.
- Water Supply Decision Support System. A tool to past and future water interactions in lower Colorado River basin.
- Spill response/Water Quality. To get better insights into the impact of spills on public health.

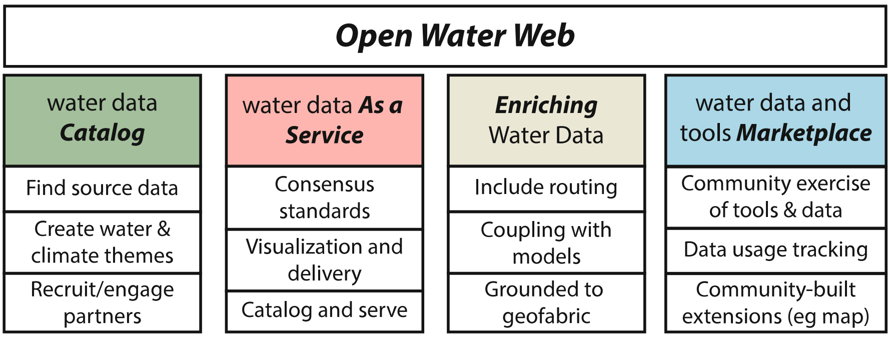

Fig. 4.7 Different components of open water web

4.7.2 Waspmote Smart Water

The Waspmote Smart Water platform contains low energy consumption sensors for real-time sensing in harsh environment for remote water quality monitoring [61]. This platform supports real-time measurements with connection to cloud online data processing. It is used for conductivity, dissolved oxygen, temperature, pH, and transparency loss. It supports following type nutrient and dissolved ions sensing:

- Fluoride (Fluoride (F^-), Nitrate ($NO_3{}^-$), Calcium ($Ca_2{}^+$)
- Chloride (Cl^-), Silver (Ag^+), Cupric (Cu^{2+})
- Potassium (K^+), Iodide (I^-), Fluoroborate ($BF_4{}^-$)
- Ammonia (NH_4), Perchlorate (ClO_4), Magnesium (Mg^{2+}),
- Nitrite ($NO_2{}^-$), Lithium (Li^+), Sodium (Na^+), Bromide (Br^-)

4.7.3 National Network of Reference Watersheds

The National Network of Reference Watersheds (NNRW) is a system of watersheds and monitoring networks with minimal disturbances [75]. These reference (pristine) watersheds are safeguarded from the impacts of human activities and related changes. These reference watersheds are used for empirical measurements of variations in water quality, physical, biological, and chemical properties of soil and vegetation. Accordingly, the data collected by these measurements is compared with data collected from disturbed watersheds to assess impacts.

4.7.4 Hydrometeorology Testbed

The hydrometeorology testbed (HMT) is a testbed at the Weather Prediction Center (WPC) [32, 135]. It is used for enhanced forecasting of extreme precipitation, and forcings, hydrologic prediction, through experiments and advanced hydrometeorological empirical observation. Schematic diagram showing the orientation of the soil probes and surface meteorological observations used at a typical soil moisture observing station is shown in Fig. 4.8. At HMT, two types of experiments are conducted which are discussed in the following.

4.7.4.1 Winter Weather Experiment

In this experiment, the precipitation algorithms are applied to various models during different weather events to observe transition zones of precipitation types. Their use is analyzed as input to manually produced empirical forecasts. The winter weather event ensemble predictability is evaluated using a tool that uses ensemble clustering.

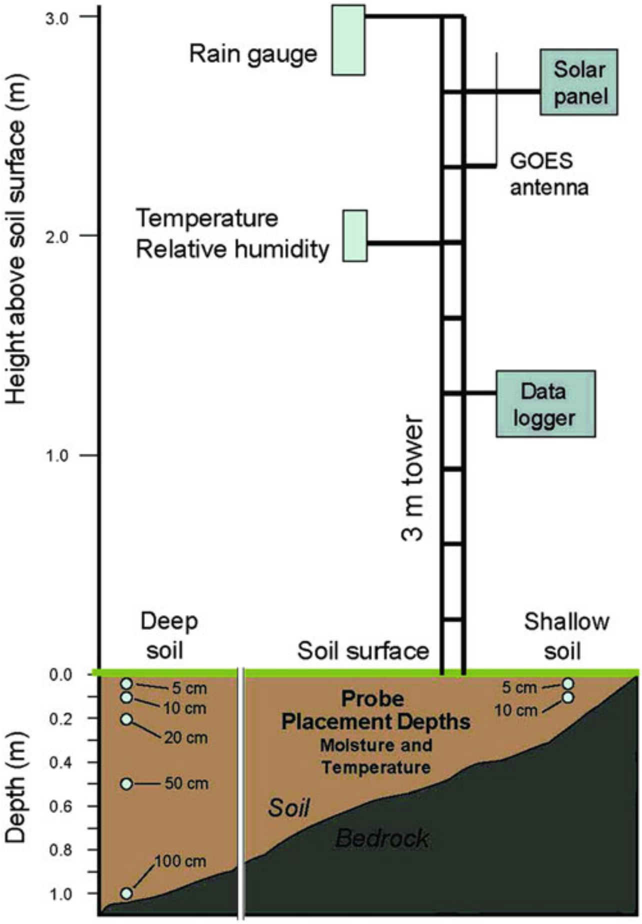

Fig. 4.8 Schematic diagram showing the orientation of the soil probes and surface meteorological observations used at a typical soil moisture observing station [135]

4.7.4.2 Flash Flood and Intense Rainfall Experiment

In this experiment, short-range flash flood forecasts are produced by using high resolution data to synthesize atmospheric and hydrological guidance. This experimental hydrologic guidance includes parameters such as runoff, soil saturation, probabilities of quantitative precipitation forecasts (QPF) exceeding recurrence intervals, and streamflow anomalies.

4.7.5 WaterWatch

The WaterWatch is comprehensive tool that provides past and current streamflow data in real time. It supports data visualization in form of graphs, tables, and maps [119]. WaterWatch is used to produce multiple stream maps with following features:

- 30 years of location data of approximately USGS 3000 streams gages
- Color maps for streamflow conditions and historical streamflow
- GUI to get stream stage (water elevation) and flow graphs
- identification of location of occurrence of extreme hydrologic events (e.g., floods and droughts)
- The real time, average daily, and 7-day average streamflow stream gage-based maps with flood, drought, high flow, and below-normal conditions
- Support for hydrologic unit code (HUC), the stream gage-based maps in hydrologic regions

A list of tools in the WaterWatch toolkit is given in Table 4.2 [117, 119].

Table 4.2 Tools in WaterWatch toolkit [117, 119]

WaterWatch tool	Description
Hydrologic unit runoff maps	Hydrologic unit runoff and runoff condition maps from 1901 to 2015
Rating curve	Streamflow rating curve
Runoff hydrograph	Runoff time-series plots
Streamflow conditions map	Streamflow conditions
Streamflow map animation	Real-time streamflow and flood-and-high flow maps
Raster hygrograph	Pixel-based plots for visualizing and identifying variations and changes in a streamflow data set
Seven-day low flow conditions	Seven-day low flow of an area for a specific period
Streamgage statistics	Statistics and a duration graph for a streamgage
Streamflow measurements	Streamflow measurements for a period and in an area
Flood-tracking chart	Flood stages with recorded peak stages of previous floods
Streamgage finder	Streamgages by region and river name
Flood and high flow	Table listing flood, high flow, and peak rank summary
Streamflow map viewer	Dynamic maps
Cumulative area-based runoff hydrograph	Graphical presentation of cumulative daily area-based runoff, plotted over the cumulative long-term statistics (median and interquartile range) of runoff
Duration hydrograph	Time-history of streamflow

4.7.6 Water Evaluation and Planning System (WEAP)

The WEAP is used for integrated planning assessments of different components of the water system and supports water planning, simulations, and water resources management tool [106]. Its robust integrated engines consider water quality, supply and demand, and other ecological parameters in single watershed, agriculture, urban, trans-boundary river basin, and environmental systems. The important features of the system include simulation capability to many different types of components such as precipitation, runoff, rainfall, reservoirs, and groundwater recharge. At the policy level, it supports demand analysis, rights and priorities, conservation, vulnerability assessment, hydro-power generation, and water quality. It can also provide the cost/benefit analysis of the simulated systems with various stakeholders engagement. The component of the WEAP is

- Water Balance. A database for water demand and supply data.
- Simulation Based. Supports simulations of various hydrologic and policy cases.
- Policy Scenarios. Policies to develop and manage water systems.
- User-Friendly GUI. A GUI to support multiple model output formats (e.g., tables, maps, and charts).
- Model Integration. Supports import and export from other models.

4.7.7 CalWater

The CalWater [27] deals with the empirical measurements of two vital factors: atmospheric rivers (ARs) and aerosols [12, 29, 81, 98, 108], in eastern Pacific coastal region. The evaluation of these two parameters is important to understand variations in extreme precipitation events and water supply. The atmospheric rivers (ARs) [27, 49, 64, 65, 73, 77, 86–89, 102, 102, 104, 121, 124, 125] deliver significant water vapor related to major storms. Similarly, the aerosols (local and remote) impact the precipitation events in these coastal areas.

4.7.8 River and Reservoir Modeling Tool (RiverWare)

The RiverWare is an advanced tool that is used for water resources modeling (e.g., river basin and reaches, reservoir, hydrologic processes, distribution canals, hydro-power production and uses, water quality, and diversions) [1]. It is also a decision making tool with real-time operations support and policy based simulations and post-processing. Another important feature of the RiverWare is the problem solution and optimization engine under temporal and spatial constraints and scenarios. For this purpose, the RiverSMART is used that is software framework to create, execute,

and archive the big RiverWare study plans based hydrologic ensemble, needs, and strategic directions of water supply and use. The policy analysis, demand input, and study manager are other important tools of RiverWare.

4.7.9 Digital Coast

The digital coast provides data and tools for coastal services including coastal water quality, land cover, shoreline, and surface water. It helps coastal management community to address climate and water related issues [76].

4.7.10 European CoastColour

The purpose of CoastColour is to provide measurements and data that is relevant to coastal zone management at 300 m spatial resolution along with processing algorithms for different coastal water types [26]. It is useful to obtain data about sea level, carbon cycle, and water mass distribution. It can also be utilized to develop and validate the various coastal water algorithms (water leaving reflectance). The CoastColour data set is available on-line.

4.7.11 Water Harvesting Assessment Toolbox

The water harvesting assessment toolbox is used in understanding and development of the water harvesting processes to meet the water related challenges [118]. It is also decision support tool to get better insights in water harvesting and supports various water harvesting techniques and system implementation.

4.7.12 National Groundwater Monitoring Network

The National Ground-Water Monitoring Network (NGWMN) is a network of groundwater monitoring wells across the US [74]. It is one of the critical networks to meet the needs of water research community about groundwater data, which is otherwise unavailable data. It supports various databases of past and current information of about water quality, water level, physical characteristics of rocks (lithology), and well composition. It is used to assess the water level declines.

A list of sustainable water IoT databases and systems with their sensing parameters is given in Table 4.3.

Table 4.3 Sustainable water IoT databases and systems

Sensing	System	Description
Meteorological data	Global historical climatology network-daily (GHCN-D)	Meteorological data from satellites and radars
Streamflow	NOAA national water information system (NWIS)	Streamflow data for water and planning purpose
Water temperature and quality	NorWest	Historical data about water temperature and quality
Chemical, physical, and biological properties	National stream internet	Geo-statistical data
Meteorological data	Quality controlled local climatological data (QCLCD)	Global Meteorological data of climate variables
Precipitation	Precipitation frequency data server (PFDS)	
Integrated water modeling	National water model	Hydrologic forecasting system of atmospheric conditions and their connection to river and streamflow
Soil moisture	Soil climate analysis network (SCAN)	Soil moisture monitoring
Snow	Snow survey and water supply forecasting	Real-time air temperature, precipitation, and snow-pack information
Groundwater	National GW monitoring network	Groundwater for climate forecasting
Wetlands	National wetland inventory 2.0	Geo-spatial data and wetland maps and properties
Water use	NWISWeb	Water use data
Atmospheric	FLUXNET	Exchange of CO_2, water vapor, and energy
Water and human health	The waterborne disease and outbreak surveillance system	waterborne disease and outbreaks
Water and aquatic animal health	National wildlife health survey database	Aquatic animal health in the wild
Daily forecast and models	Network for environment and weather applications	Interactive forecast models

4.7.13 Water Toolbox

The water toolbox is a data portal for integrated water resources management. It provides state-of-the-art tools, models, best management practices, legislative resources, policy guidelines, and comprehensive data sets to the international water community for education and research purpose.

Other water related tools to support real-time decision making in sustainable water IoT are discussed below [112]:

- SSMI Water Vapor Imagery. Latest integrated water vapor, cloud liquid water, and rain rate.
- GOES West Satellite Imagery. Infrared, visible, and water vapor satellite images.
- AR Precipitation Observations. Gridded precipitation products at several timescales.
- Atmospheric River Observatories. Analyses of water vapor flux, radar and disdrometer, and snow level.
- Integrated Water Vapor. An experimental tool using NCEP's GFS and NAM systems
- Probabilistic Landfall Tool. The magnitude, probability, and timing of West Coast AR conditions.
- Integrated Water Vapor Flux. An experimental tool using NCEP Global Forecast System.
- Precipitation Forecasts. The quantitative precipitation forecasts from NCEP/WPC & GFS.

4.8 Sustainable Water Indices

The major indices are given below:

- The water footprint. The water footprint is an index of the volumes of freshwater appropriated/consumed/polluted by the humanity. Its measurement is presented by using the matrix format at spatio-temporal scale. The water footprint combined with other economic, social, and environmental data is a good indicator of water sustainability including SGD goal assessment.
- The U.S. Climate Extremes Index is a US index of extreme conditions. The long-term values of this index indicate the tendency for extremes climate.
- Watershed Analysis Risk Management Framework (WARMF). The Watershed Analysis Risk Management Framework (WARMF) is a general tool to model and analyze the watershed and can be used with different watersheds. It is utilized for short- and long-term prediction process, management of watersheds, and in calculation of total maximum diurnal load.

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Chapter 5
Internet of Things for Sustainable Forestry

Abstract Forests and grasslands play an important role in water and air purification, prevention of the soil erosion, and in provision of habitat to wildlife. Internet of Things has a tremendous potential to play a vital role in the forest ecosystem management and stability. The conservation of species and habitats, timber production, prevention of forest soil degradation, forest fire prediction, mitigation, and control can be attained through forest management using Internet of Things. The use and adoption of IoT in forest ecosystem management is challenging due to many factors. Vast geographical areas and limited resources in terms of budget and equipment are some of the limiting factors. In digital forestry, IoT deployment offers effective operations, control, and forecasts for soil erosion, fires, and undesirable depositions. In this chapter, IoT sensing and communication applications are presented for digital forestry systems. Different IoT systems for digital forest monitoring applications are also discussed.

5.1 Introduction

In the field of agriculture, there has been a lot of development in soil moisture capability improvements and system design. However, soil moisture sensing in forests is lacking [53]. There are big gaps in data collection in forests and rangeland systems, particularly in 640 million public lands in the USA that also includes grazing lands and reserves. 33% of the water comes from these lands which is supplied to the community in the Western US. Loss of forests through droughts and fires will significantly impact the water supply [43]. This fact underscores the importance of sustainable forests for survival of human life [47].

In twenty-first century the climate is changing dramatically [66, 73, 98]. The average temperature has increased by 1.8 F from 1901 to 2018. This average increase in temperature with same amount of precipitation has resulted in increase in evaporation rate [2]. This increase in temperature is highly correlated with the forest fires [58, 99]. In 2018 and 2019, the State of California in the USA witnessed a very significant fire season [80]. Out of this 1.8 F averaged increase, 1.2 F increased in the last three decades from 1989 to 2019. This rapid increase has caused many

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disturbances in the forest ecosystem which is leading to extreme cases of shortage of water or abundance of water that system is unable to handle [33, 62, 67, 98].

The IoT hold strong promise for digital forestry [105] applications. An efficient management system can be developed for effective resource management and decision making in forest inventory, in situ and remote soil sensing, and forest fire prediction and control. Forest fires are another threat to sustainable forest management. In the USA, 8000 kilo hectares were burned in 2015 due to forest fires [80]. The IoT technology in forest environment can be used to sense, communicate, analyze, and to make informed decisions for sustainable forest management. Currently, technology is being used in digital forest management. However, the applications of the technology in the forest management lack well-integrated systems for real-time sensing and decision making. IoT has the potential to fill this gap through its well-connected and integrated sensing and communication components.

Moreover, the presence of droughts in the entire forest landscapes [18] (short-term in agriculture, and prolonged droughts [101] in the entire ecological system [29, 31]) present a major challenge. These two drought systems are connected because of the flow of water from the forested mountains to the agricultural lands in the plains [90, 94]. In the ecological drought scenario, the drought progression over time leads to accumulation of droughts on the landscape in the time span of multiple years. Forests have the ability to survive only up to 2 years of drought that extends to 3 years for very healthy forests. After this forests lose their ability to resist insects and diseases which contribute to rapid forest loss. Although it can be argued that because of the water-limited forests systems, this huge amount of biomass cannot be sustained. However, development of early warning IoT systems in forests and rangeland with ability to sense soil moisture, detect and predict water patterns can play a vital role in sustainable forests. Such systems with adaptive capability can inform important decisions such as how to plant and when to reseed. These functions of IoT for sustainable forest management are discussed in the next section (Fig. 5.1).

Furthermore, when a forest is burned it has to be replanted in a very short time span of 2–3 years in order to prevent proliferation of the invasive grass. Therefore, in the forest restoration, the knowledge of seeding conditions and weather pattern becomes utmost important [44]. Due to expensive native seeds, the seeding carried out in poor conditions causes the wastage of valuable resources and times imaging the forest restoration process. Seeding without considering the soil moisture data and short-term weather projection have the success probability of less than 50%. The IoT system in forests can provide this data in real time, hence increasing the success rate of the restoration process.

Additionally, roads in the forest systems are also vulnerable to flooding, landslides, and mudslides after the fire event [17]. The potential risks of these events include burial roads in mudslides and destruction of bridges. An accurate prediction of these events though IoT sensing and communications makes the IoT monitoring a useful tool for sustainability and restoration. Particularly, the upper and lower watershed monitoring is not fully developed. There is need of IoT solutions containing connected weather and soil moisture stations integrated to the cloud for real-time decision making in forests. These can inform hold and absorb decisions

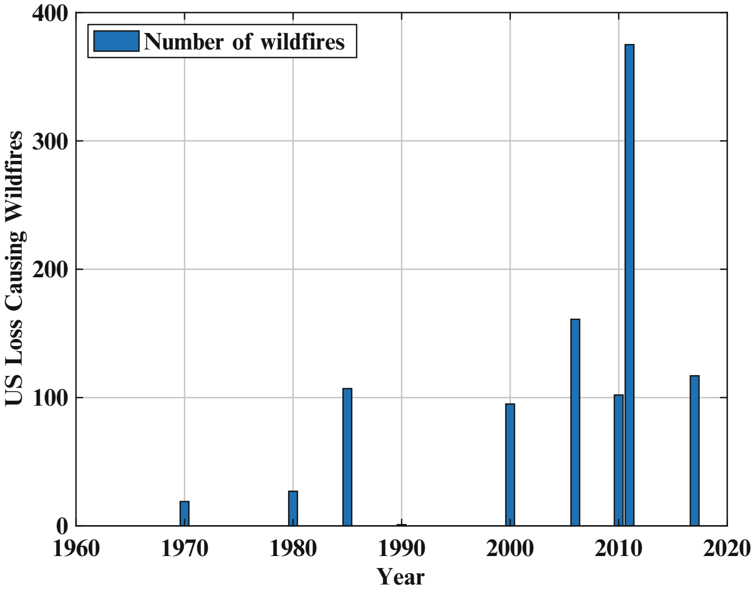

Fig. 5.1 The yearly data of the US wildfires

in the case of big rain events in the upper and lower watersheds. Such IoT systems for digital forestry can bring significant improvements in the areas of climatology, hydrology, and vegetation.

5.1.1 Sustainable Digital Forestry

The UN's sustainable development goal number 15 is related to the forest management and entails terrestrial ecosystem's protection and restoration [7, 93]. The environmental benefits of the forests for the sustainability future span multiple SDGs (see Fig. 5.2) and support natural development of the ecosystem. Forests are the biggest absorbents of fossil fuel caused carbon dioxide (CO_2) emissions [86]. To avoid the reduction of the CO_2 better forest management practices are required. Currently, the biggest challenges faced by the forest ecosystems include droughts, diseases, insect infestations, and high fire-caused tree mortality [101]. The bioenergy technique to meet energy needs by producing biofuels from organic sources such as biomass also underscores the need of restoration of forests. Other important digital forest management factors include land use and ownership, the global scope of forest markets, forestry markets, advancements in biopower technology, forest policies and regulations. These challenges are discussed in detail in the following section.

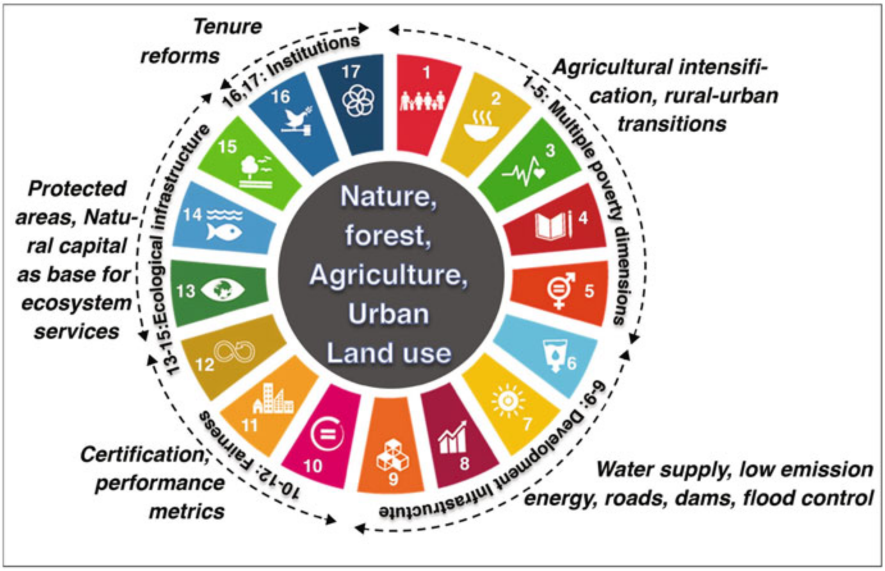

Fig. 5.2 The SDGs and forestry [93]

5.1.2 Challenges in Sustainable Digital Forestry

The digital forestry is defined as:

> Digital Forestry is a framework that links all facets of forestry information at local, national, and global levels through an organized digital network [105].

There are many challenges in the area of digital forestry including changing climate, human caused disturbances to the forests [52], wildfires [57], and invasive species [13, 24, 107]. These are explained in the following:

- The increasing number of fires, insects, and fragmentation are a major challenge to achieve sustainability, and these also leads to decrease in biodiversity. The diseases and insects are causing huge losses to the biomass. The water quality, quantity, and storage capacity are arising. The wildland–urban interface (WUI) [98] is a zone in which forest and homes intermix. This intermixing is a major source of wildfires, disease spread, habitat loss, biotech invasion, subsidized wildlife, and fragmentation [22, 65, 79]. The wildland–urban interface also poses a threat to forests in terms of the forest predators due to availability of abundant sustenance in WUI. To control and reduce the number WUI-caused predators, there is a need of monitoring and elimination of their nesting and perching

sites, invasive trees and unused poles, and other structures by placing a ban on establishment of water facilities, dumps, and garbage in WUI. These predators include species such as crows, ravens, coyotes, magpies, foxes, raccoons, skunks, and other species [10].
- The adaption of sensing and communication technologies in digital forest management practices is lacking. Adoption of these technologies has huge potential to improve sustainable management of forests through development of decision support systems at large spatial scales in a timely manner [23].
- A related consequence of lacking of technology adoption is unavailability of accurate inventory forests [56]. Without the information of forest sources, it is hard to design and implement sustainability initiatives. The non-native insects and other diseases and pests which feed on trees are causing significant tree mortality. The lack of technology implementation is hindering assessment of the impact of these species on the ecosystem.

To overcome, these challenges in digital forest management, multi-pronged efforts are needed at different levels including forest managers, policy makers, scientists, and researchers. The technology can fill the gaps in forest data management and resource inventory by providing reliable data which can be used to create maps, and other reports of resource assessment [85]. Accordingly, the real-time support systems can be developed for data analysis, sustainability, and actuation. Major data needs for sustainable forest management includes:

- Forest health and diseases [92]
- Biomass and forest fuel loads for renewable energy [75]
- Forest carbon stock and sequestration [49, 83, 89]
- Forest species including invasive [13, 24, 107]
- Fires and water data [63]
- Forest inventory [14]

Moreover, coupled with the data needs are modeling and analysis techniques developed based on the data and inventory. The development of such decision making systems will also inform land-use decisions, their impacts and benefits to forests and grazing lands [48]. These analysis techniques can then accordingly be used for pattern prediction and quantification, measurements, valuation, monitoring and assessment of emerging threats and challenges. The IoT for sustainable forest management can overcome these challenges through real-time sensing of the forest ecosystem. It is presented in the next section.

5.2 IoT in Digital Forest Management

The sustainable forestry IoT through its communications, sensing, and systems technologies has the great potential to improve the resilience of forests. It can also reduce the impact of climate change on the forestry ecosystem [11]. Accordingly,

it can provide bioenergy sources from biomass which will bring energy and economic prosperity to community while reducing stress on the fossil fuels. The nanotechnology applications will bring improvements in woods [46]. Moreover, detailed watershed insights can be gained (e.g., water resources, pollution, water shortage, water quality, and futuristic water and rain and patterns). Digital forestry IoT has the potential to meet the real-time needs of forest, grazing land, range managers. These include:

- IoT early warning systems for drought stress to initiate and prioritize actions
- Forest soil moisture sensing is used for informed restoration decisions
- The snowpack change detection to plan annual water management and to accordingly adopt effective management practices
- Grazing land productivity changes and projections to guide herd and range allotment
- Real-time sensing and detection in forest covers for informed changes in forest management policies and practices

5.2.1 Elements of the Forest IoT

IoT can be used to connect the upper watershed and user community in a systems approach. Soil moisture sensing and communication systems can be integrated with soil moisture collection system in forested areas. Moreover, the forest drought monitor interconnected with IoT and cloud can provide real-time forest observations for real-time decision making by government agencies. Overall, IoT has the potential to fill the gap in forest soil moisture and impact information with advanced sensing and communications technology.

The IoT in digital forestry envisaged to have the following elements:

- Ability of real-time state-of-the-art data collection and wireless transmission of physical, chemical, environmental, and biological factor at the forest sites scattered across geographical, vegetational, and climatically forest zones.
- Systems to motoring of soil, climate patterns.
- Storage of data in the cloud and real-time access to the decision making through the visual interfaces.

5.2.2 Forest Things

The things of the forests IoT are outlined below:

- Invasive Species. The current needs are related to minimization, reduction, and elimination of invasive species from being introduced, established, and spreading [13, 24, 107].

- Inventory, Monitoring and Analysis. The requirements are availability of resource data, analytic, decision tools for efficient and reliable identification of the status of forest resources, insects, diseases, and fires, and forecasts, and trends for sustainable management [8].
- Land use and Recreation. Forests are major sources of community recreational activities, such as hiking, camping, fishing, canoeing, and skiing, and play an important role in sustainable community health. The land use and management decisions impact these activities [97].
- Wildland fire, Wildland–urban interface (WUI) [98]. For these, the emphasis is on minimizing the determinant impact of fires and enhancing the beneficial effects of fire. Moreover, the WUI posed challenges to forest (e.g., fires and predators). Therefore, any forest decisions and their trade-off related to these needs to be well thought to minimize any negative effects.
- Water, Air, and Soil. Forests and grasslands play an important role in water and air purification, prevention of the soil erosion, and in provision of habitat to wildlife [78].
- Wildlife. The current focus in this area is on getting insights on complex interaction between species, ecosystem processes, emerging threats, land use, and management [45].
- Other things include agroforestry, forest products, landscape management, and operation [95].

5.2.3 The Montréal Process Criteria and Indicators (MP C&I)

In this section, the Montréal Process Working Group [41], its criteria and indicators for sustainable forest management are discussed.

5.2.3.1 Montréal Process

The Montréal Process Working Group consists of multiple representatives from different countries to address the issue of sustainable forest management. The working group was established in 1994. It has developed stipulatory criteria and indicators for forest sustainability and conservation of both boreal and temperate types of forests. Its members are different socio-economic and ecological conditions. They are collaborating on forest monitoring, sustainability, and assessment issues. These members are from the regions that have significant presence of temperate and boreal forests. These countries are:

- The USA
- Argentina
- Australia
- Canada

- Chile
- China
- New Zealand
- Russian Federation
- Japan
- Korea
- Mexico
- Uruguay

5.2.3.2 Criteria and Indicators (MP C&I)

The Montréal Process criteria and indicators (Montréal C&I) [42] are used to collect sustainability and conservation data of temperate and boreal forests for the purpose of assessment, monitoring, and reporting. These criteria and indicators (7 criteria, and 54 indicators) together present a comprehensive sustainability framework reflecting the vital components of forestry such as conditions, biological diversity, ecosystem health, soil and water resources of forests. As this criterion treats forests as ecosystem, hence, it enables robust range of socio-economic, environmental services and benefits. Accordingly, the MP C&I facilitate the regulations and policy development to achieve sustainability in forests. The seven criteria are shown in Fig. 5.3.

5.3 Sensing in Digital Forestry IoT

In this section, different methods of sensing which are applicable to the forest environment are discussed.

5.3.1 Remote Sensing

Applications of the remote sensing approaches in digital forestry offer many benefits as compared to the in-situation sensing. With a sensing unit of 10 m to 40 km, the remote sensing can be used cover area of up to 1000 km [5]. Therefore, a large geographical forest zone can be managed with this technique. Moreover, accurate maps can be produced for efficient decision making. Currently, NASA is running missions for soil moisture measurements. The aim of these missions is to obtain high resolution maps of soil moisture with multiple revisits of the target sites. In digital forestry, this can be used to investigate processes of terrestrial carbon, energy, and water cycles. It can sense energy and water flux in the forests. Moreover, enhanced drought predictions can be made using these missions. It can also be used to quantify the forest landscape carbon flux (Table 5.1).

Fig. 5.3 The Montréal process criteria and indicators

Table 5.1 Satellite systems for remote sensing of soil

System	Frequency	Resolution
The Advanced Microwave Scanning Radiometer—Earth Observing System (AMSR-E)	C, X-band passive	25 km
The Advanced microwave scanning radiometer 2 (AMSR2)	C, X-band passive	25 km
WindSat—US Naval Research Laboratory	C, X-band passive	25 km
The Advanced Scatterometer (ASCAT)	C-band active	12.5 km
Soil Moisture and Ocean Salinity (SMOS)	L-band passive	25 km
Soil Moisture Active Passive (SMAP)	L-band passive	3–36 km
Cyclone Global Navigation Satellite System (CYGNSS)	L-band reflectivity	1–3 km
SAtélite Argentino de Observación COn Microondas (SAOCOM)	L-band active	1 km
NASA-ISRO Synthetic Aperture Radar (NISAR)	Ka-band	200 m

Remote sensing in digital forestry is insufficient due to vegetation thickness. The sensing depth by limited to few centimeters. It further decreases with increase in measurement frequency. Moreover, the vegetation loss also increases with increase in the measurement operation frequency.

The radar and LiDAR based active sensing approaches [61] can also provide useful information. Radar operates at 1.26 GHz frequency with VV, HH, and HV polarization and has resolution of 3 km. The radiometer functions in 1.41 GHz with polarization of H and V, and has resolution of 40 km. Although radar in comparison to radiometer has high spatial resolution (1–3 km) but it is more sensitive to surface roughness and vegetation. There it has limited accuracy in thick forests. However, radiometer has high accuracy because it is less impacted by the surface roughness and vegetation but coarser spatial resolution of 40 km makes it less useful for small geographically separated forests. An alternative of combined radar and radiometer solution gives enhanced results of improved resolution and higher accuracy to meet IoT sensing requirements in digital forestry.

Overall, remote sensing can be used to obtain important data from the forest soils and vegetation. This includes spatial coverage of the vegetation, classification of forests, and soil moisture [61].

5.3.2 *Per-Tree Based Forest Analysis*

High spatial resolution combined with aerial photography approaches can be used to analyze the forests on per tree basis. For this approach to work, less than 0.5 m pixel size is required. Machine learning based image processing techniques are useful for remote sensing based tree detection and delineation approaches. Popular tree delineation methods include local maxima [96], boundary following [54], template matching [69], region based segmentation [102], and model based methods. Extension of these approaches is also used for species genesis.

5.3.3 Phenology Sensing

In phenology monitoring, the impact of environment instigated events (e.g., the temperature and length of the day) on the plants and animals life spans is studied [39, 76]. The study consists of the flowers blooming in the autumn season to color change patterns and subsequently falling of leaves in the fall season for the plants (Fig. 5.4). For the animals, this includes analysis of bird migration patterns and insects hatching activities. Previously the phenology monitoring activities such as forest canopy monitoring were conducted manually on leafs by recording their temperature and color change manually during different seasons [106]. For automated monitoring purpose IoT systems offer a strong monitoring potential. An IoT based automated leaf monitoring system has been developed that is based on cameras and offers image capturing and automated analysis in the real-time. The sensors used in the system can capture multiple colors by using different channels with abscission, coloration, and automated senescence tracking. These systems hold a promise for automated phenology monitoring in the forest environments.

5.3.4 Forest Species Sensing

An analysis of the species habitats in the forest environments is important to assess the impact of forest loss due to fires, droughts, and climate change. Ecological monitoring in the forest environments is a laborious job for human researchers. Often time such efforts require sitting in the field for hours to record birds species in forests. This increases when multiple species are under study requiring multiple experts to record multitude of sounds. The forest IoT system holds promise in this area of automated species monitoring. A monitoring system has been developed to monitor birds with the capability of listening to multiple birds at a time [16]. This system offers a detailed real-time activity of the birds such as bird arrival and departures from their nest, information about location and nesting pattern changes. The system is based on the multi-label and instances and can also be used to identify drops from the rain fall events and human tree cutting and tree falling from the natural events. Currently, it has been tested to work with different species such as frog, grasshopper, crickets, and marine mammals. Major changes include interference from the natural and human noises in the forest environments. Moreover, the bat wings are also being used for monitoring bat populations.

5.3.5 Species Migration Monitoring

A knowledge of the bird's migration patterns can provide useful information to save endangered species and can help in conservation efforts. One such IoT system

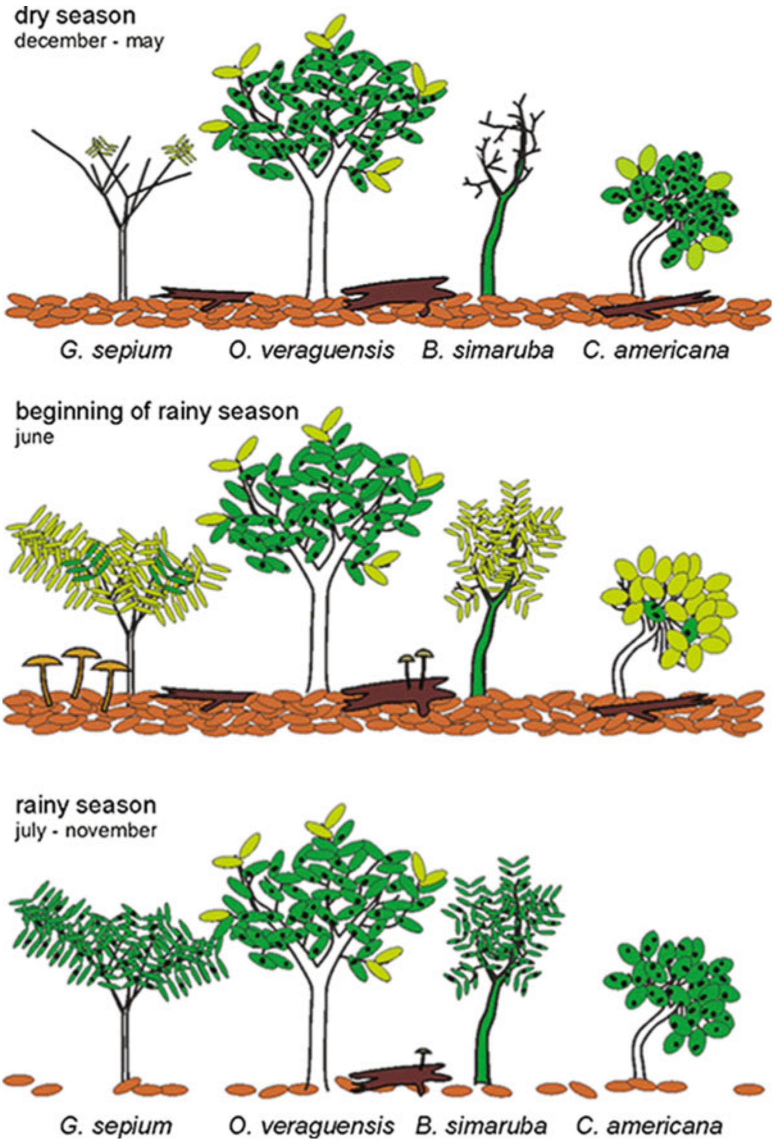

Fig. 5.4 A schematic representation of vegetative characteristics of Gliricidia sepium and Bursera simaruba (both deciduous), Ocotea veraguensis (evergreen), and Curatella americana (brevi-deciduous) at different times of the year [76]

has been developed to monitor Grus Americana (the whooping crane), a Native American bird species in danger of extinction with current count of fewer than 550 birds [3]. This system provides detailed environment and behavior of these birds to

Table 5.2 Number of in situ soil moisture sensing stations in US

Soil moisture measurement systems	Stations	In forests	Percentage
Snow Telemetry (SNOTEL)	445	289	64.9%
U.S. Climate Reference Network (USCRN)	147	18	12.2%
Soil Climate Analysis Network (SCAN)	219	26	11.9%
The Automated Weather Data Network (AWDN)	59	1	1.7%
The U.S. Regional Climate Reference Network (USRCRN)	16	4	25.0%
Delaware Environmental Observing System	42	8	19.0%
Environment and Climate Observing Network (ECONet)	42	6	14.3%
Kentucky Mesonet	23	4	17.4%
NOAA's Hydrometeorolgy Testbed (HMT)	178	35	19.7%
New York Mesonet	126	13	10.3%
Oklahoma Mesonet	141	2	1.4%
Soil moisture Sensing Controller and Optimal Estimator	155	39	25.2%
Georgia Mesonet	86	5	5.8%
Other networks	223	0	0.0%
Summary	1902	450	23.7%

inform migration patterns by using sensing and communication devices attached to the birds. Through these IoT devices real-time information is obtained about every move of the birds (Table 5.2).

5.3.6 Tree Health Sensing

The tree health sensing is done by detecting changes in vital metabolites and cellular functions for early identification of stress [30]. Moreover, it can also be assessed by analyzing the relationship of nitrogen in plants and soils. The high levels of ammonium nitrate and ammonium sulfate (that contains sulfur and nitrogen) are applied. Accordingly, the relationship between nitrogen assimilation and photosynthesis is analyzed. Moreover, the stress exposures also lead to production of anthocyanin production.

The metabolic stress can also be used as an indicator in different trees [30]. By using this approach the low and high risk areas can be identified which can be used to decide treatment options. The tree metabolism and genomics are two approaches for stress sensing. They are related to the genes of the organism understudy. This is also useful to establish long-term indicators for climate related events. Similarly, in polyamine metabolism, the physio-chemical stress related genes are separated and characterized at single plant level, which is then expanded to multiple trees. Accordingly, the impact of disruptive variations in single metabolite and their interconnections can be identified, which can be used to engineer resilient biosynthetic genes to grow healthy plants.

The forest health also depends on photosynthesis, microbial diversity, and soil quality [23]. These factors are impacted by the nitrogen, calcium, and aluminum. Therefore, sensing of these parameters is also important to assess tree health and lack of these can be used to inform customized improvement techniques. These health sensing approaches are useful in scenarios where visual analysis either does not work or yield unreliable results. Accordingly, appropriate treatment actions can be taken before it becomes too late. Moreover, the satellite spectral trajectories can be used to map forest health related variations caused by fire, insects, land use, disease, wind, and harvesting. Furthermore, the tree mortality can also be done using aerial data collection and surveys to assess the area and intensity. This data is utilized to eliminate hazardous tree and fuel reduction before the fire season.

5.3.7 Sensing of Increased Soil and Air Temperature and Elevated Carbon Dioxide

The soil and air temperatures are good indicators of the climate induced variations and wetlands. For this purpose, a testbed has been designed to house different types of soils at field conditions. These soils are exposed to various controlled temperatures and different levels of carbon dioxide to assess the changes in the organisms [21]. The experiment outcomes are discussed in the following:

- This provides useful information about the physiology of plants under high carbon dioxide levels [9, 72].
- The insights about the relation between the underground warming due to temperature increase and corresponding increase in greenhouse gases can be provided [1, 12, 38, 64].
- Accordingly, the suitable soil and air functions for different environmental organisms can be established.
- Moreover, through these empirical analysis, climate related threat and stress and threats to biogeochemical and hydrological services of the ecosystem can be answered.
- Furthermore, the better models can be established for enhanced forecasting, mitigation, and adoption response to environmental changes.

5.3.8 Illegal Logging Sensing

The illegal logging is a major cause of degradation in forest ecosystems and leads to biodiversity losses and deforestation [36]. The sensing of the illegal logging can be done using microphone sensors which can sense logging related sounds such as saws, axes, and transportation. Accordingly, by using the wireless communication links this information can be communicated in real time to forest control centers for proper enforcement actions.

5.3.9 *Fire Sensing*

The fire sensing is discussed in detail in this section. First the impact of the fire on soil is presented [40].

5.3.9.1 Impact of Fire on Soil

The forest fires have many negative impacts on the forest ecosystem.

- Due to prolonged presence of the long chunks of timber, the underneath soil is exposed to acute heat which impacts the soil physical, biological, and chemical properties.
- The soil microbes are also eliminated depending on the burn-extent because of the severe heat. The decreased amount of nutrients is detrimental to the vegetation growth and leads to staggering recovery.
- The structure of soil and texture is also impacted.

Due to these long-term impacts of the intense soil heat, the understanding of these soil dynamics bio-geo-chemical processes is important for proper forest management practices. In this regard, the advanced DNA sequencing approaches are being considered for soil recovery after soil burning.

5.3.9.2 Fire and Environmental Pollution

When the height of the smoke coming from the fire exceeds the near-surface boundary layer, the pollution concentration starts. The fires in boreal forest have intense energy as compared to temperate forests. Therefore, these smokes tend to go well beyond the boundary layer. At those elevations the negative impacts of those smokes include prolonged stay in atmosphere, wider horizontal and downward vertical transport, health related impacts such as asthma and eye burns. The HRRR-Smoke model is fire smoke forecasting model for height and travel direction prediction of near-surface boundary layer smoke.

5.3.9.3 Impact of Fire on Fresh Water and Stream Flow

The wildfires not only impact the soil, but the water supply is also impacted by the fires. The preservation of the fresh water resources is important to achieve sustainability. These wildfires impacts and risks include:

- Watersheds damages and hydrological disturbances
- Soil erosion after extreme rain events
- Sedimentation
- Ecosystem degradation

The models for hydrological disturbances framework are shown below [32]:

- Change point model (CPM)
- Double-mass analysis of precipitation and streamflow (DMC)
- Precipitation duration curves (PDC)
- Flow duration curves (FDC)
- Watershed climate elasticity model (CEM)
- Water Supply Stress Index model (WaSSI)

5.3.9.4 Fire Sensing and Danger Estimation Tools

The fire danger can be estimated based on different measurements which include:

- Using the light detection and ranging systems (LiDAR) for forest structure, carbon loss, smoke emissions, and dangerous fuel loads [104].
- Moreover the real-time measurements of moisture can be taken using a system of networked towers deployed for this purpose. These towers are also used to take other vital measurements of carbon dioxide, the eddy fluxes of energy.
- A sonic detection and ranging system (SODAR) to measure wind speed and direction at different heights can also provide useful information about the fire spreading danger and potential directions [19].
- The aircraft teams and satellites are also employed to get useful remote sensing data for fire management decisions and teams on the ground make the best decisions possible. This airborne and satellite observation [51] is very useful to understand the intensity, perimeter, frequency, spread for burning forest fires. With the advancement in technology and heat signature detection algorithms, the advanced radiometers with very high resolutions are able to detect tiniest fires from the space. The impact of the fire on the spatial structure of forest in Yosemite National Park using airborne LiDAR and satellite data is shown in Fig. 5.5.
- The Moderate Resolution Imaging Spectroradiometer (MODIS), Visible Infrared Imaging Radiometer Suite (VIIRS), NOAA's GOES-16, GOES-17 geostationary satellites, Joint Polar Satellite System's NOAA/NASA Suomi-NPP and NOAA-20 satellites are the satellites and tools used for remote sensing of the fire. These works on the principle of detection, radiation, and reflection of the signal, and can operate both in daylight and night times by sensing the low intensity visible light of fires. Moreover, by using the special equipment with multiple cameras can be used to detect fire flame plume composition.

  The IR based heat sensors can overcome some of the limitations of the satellite based fire detection with such low accuracy of perimeter and location, lack of capability to distinguish between fires and smokes, inability for fire intensity interpretation due to dense smoke layers which act as a curtain [59]. The National Infrared Operations Program (NIROPS) airborne sensing system utilizes infrared based heat sensors. This system has the capability to sense 6 miles under it with 6 in. resolution at 1.89 miles flight altitude. It can map 468.75 square miles in an hour. By using the compressive sensing approaches, the data is transferred in

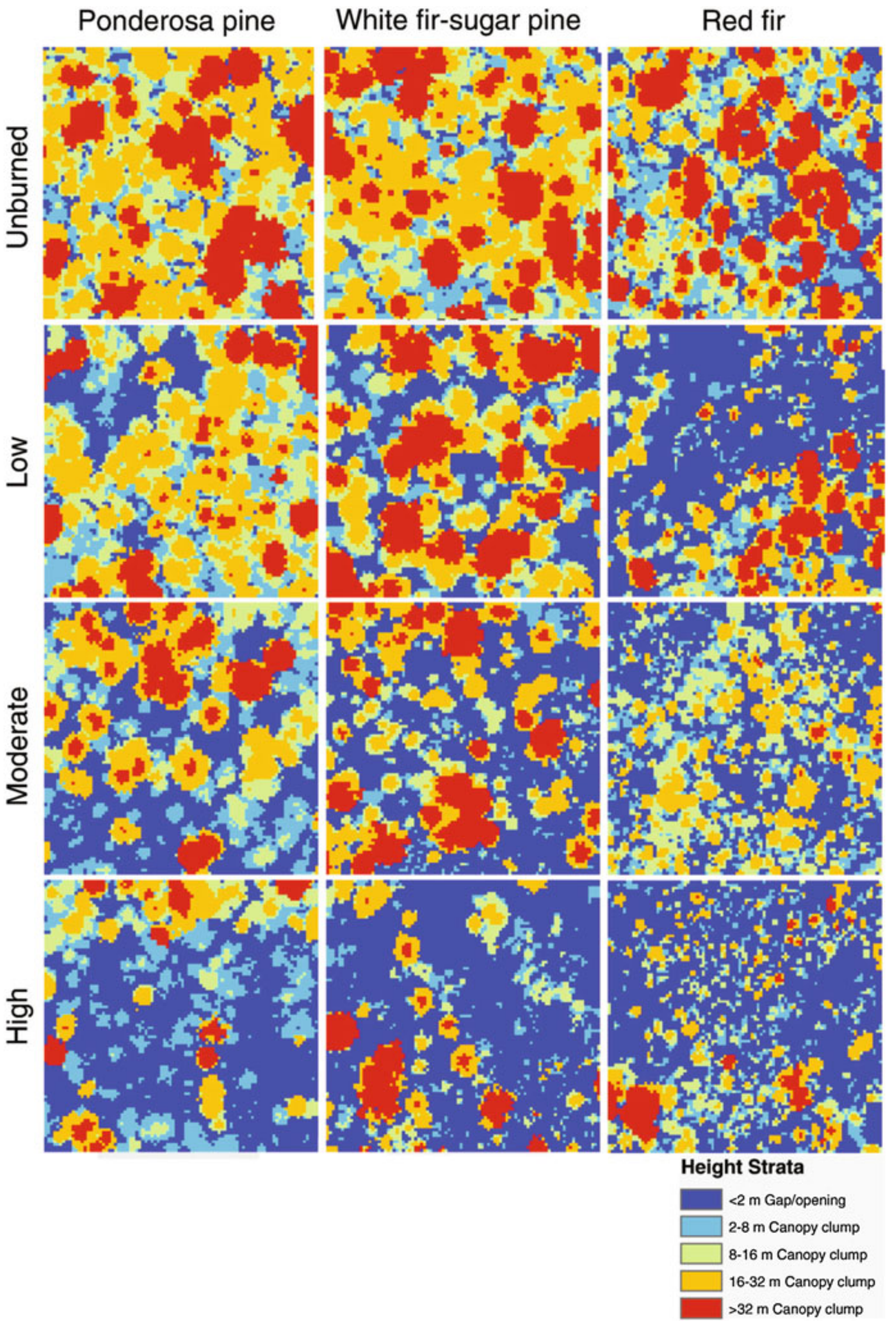

Fig. 5.5 The impact of the fire on the spatial structure of forest in Yosemite National Park using airborne LiDAR and satellite data [51]

real time to the base stations [6]. These sensors work much better at night time as compared to daytime due to the absence of sun glint interference. Currently, there is a need of wider area infrared sensing technologies to reduce the flight times.

These measurements combined with past climate data, current indices (e.g., Hot-Dry-Windy Index—HDW), and moisture data and models can produce highly reliable estimates of the fire danger. Accordingly, the maps can be developed for mitigation approaches to assist firefighters and fire mangers. Accordingly important decisions such as evacuation orders and smoker jumper's dispatch can be made. This systems uses both climate and vegetation data for assessment of fire risks, transitioning to the canopy, where they are much more difficult and expensive to suppress. Moreover, the prescribed fires can also be used to reduce the danger of overhead fuel.

5.3.9.5 Remote Sensing of Amazon Rain Forest Fires

The forest fires sensing can be done using the satellites, where the IR sensors are used to detect the infrared radiation emitted by wildfires. The remote sensing of the 2019 Amazon rain forest fires has shown that these fires started from forest lands that were cleared for the purpose of agriculture and planting. The satellite image of the Amazon fires is shown in Fig. 5.6, where the fires are shown in red color, the forest in shown in green color, and the deforestation is depicted in yellow. The land use and rapid deforestation of Amazon are major environmental issues. Because these are not caused by the natural phenomena rather human activities is a major causation of these fires.

The remote sensing of wildfires has many benefits:

- The real time and enhanced fire monitoring can be done at large geographical areas. Accordingly, this information can be used by fire managers in real-time
- The fire weather data and relevant fire danger alert systems can be developed by using predictive modeling approaches
- The aerial fire control fuel loading management policies can be developed for fire mitigation
- The smoke thickness and movement can be predicted to prevent health related consequences due to smoke inhaling

5.3.10 Invasive Species and Fungi Sensing

The invasive non-native exotic species are a major challenge in forest managements. These species present major ecological challenges and advanced sensing and

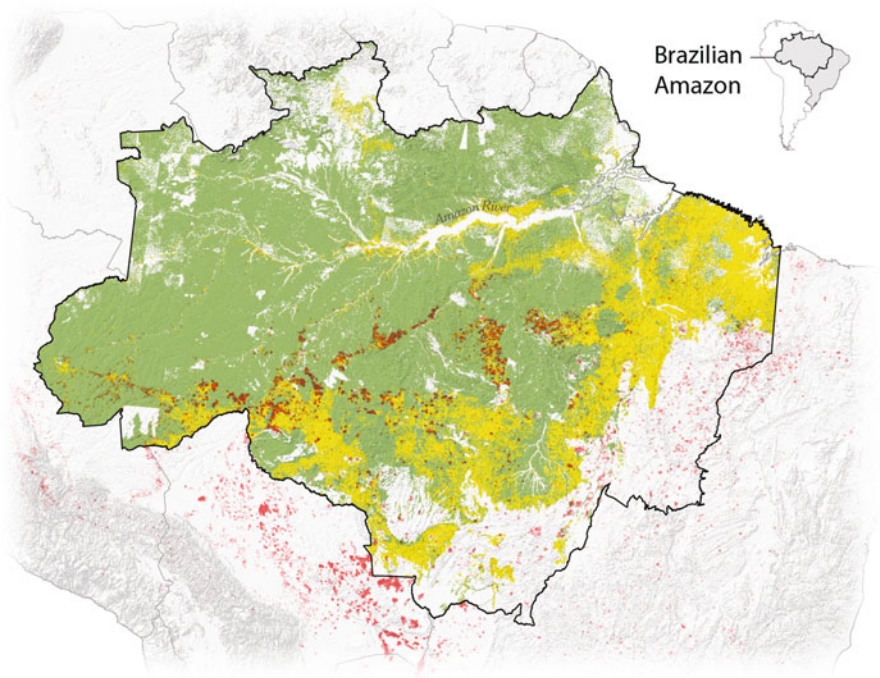

Fig. 5.6 The satellite image of the 2019 Amazon fires shown in red, the forest is shown in green, and the deforestation is depicted in yellow based on NASA data

monitoring approaches are needed to reduce, eliminate, and minimize the impact and spread of invasive species. Their mobility medium is generally the lumber, firewood, and forest vehicles. These mitigation and sensing approaches span across multiple areas [37] such as:

- Sensing of alien pests in forest
- The treatment of hardwood logs for removal of pathogens and insects
- Short for silviculture of allegheny hardwoods
- Pest management with Bacillus thuringiensis
- Biological control, and genetics management
- Technology to reduce impact

Moreover various types of fungi related with the tree also present a conducive environment for invasive species, which outnumbers native species. Moreover, these also lead to wood decomposition. Therefore, fungi sensing becomes important for invasive species management and also for sustainable forest management and restoration [47]. The white rot fungi is also related to carbon cycle of forests and causes detoxification, transport, intense cell walls degradation (e.g., recalcitrant polymer and lignin). These also have the protection for biofuel conversion for bioenergy [28, 35, 88]. The various types of approaches can be used to identify

the fungi such as molecular and microscopic. The genetic sequencing is also used to inhibit soil related fungi. The GenBank is an example of sequencing database. The Scanning Electron Microscopy (SEM) [4] approach is utilized for wood decay. The computer tomography (CT) and ground-penetrating radar (GPR) are also utilized for fungal decay and moisture detection providing information into the wood structure. The DNA analysis is also conducted for pathogen identification. The wood metabolite profiles can also be determined by using the time-of-travel approach (direct analysis in real-time (time-of-flight) mass spectrometry DART-TOFMS). These sensing approaches will provide deeper insight into the fungi wood relationship in sustainable forest IoT.

5.3.11 Vegetation Height Sensing

The airborne LiDAR provides an accurate estimate of vegetation height. This approach operates by transmitting the laser beam in the vegetation to the ground. The reflected energy from the vegetation is detected to assess the vegetation height, density, and structure. This sensing approach is used to identify the area for birds habitat related decision making. Moreover, the vegetation change tracker (VCT) [71] can also produce reliable forest estimates using satellite images.

The tracker uses an autonomous program for mapping using the Landsat data. The resulting maps can be used to distinguish forested and non-forested regions. Currently, in ground based mapping systems, the false indicators of forest disturbances are a major challenge in forest management particularly in wetland and agricultural landscapes. This trackers also helps to identify those false positive through improved mapping.

The TimeSync is another systems which uses over 30 years of satellite data to analyze the variations in vegetation status over temporal scale by using the time-series modeling approach [100]. The high correlation with the drought periods and decrease in fresh canopy has been identified. It has been shown that the decay depends on the length and intensity of the short-term summer droughts and other factors such as:

- Geographic variation
- Structure and composition
- Soil and topography
- Insect and disease outbreaks

5.3.12 Machine-Induced Stress Sensing

The forest machinery and equipment affect the soil in forest and change physical properties of the soil, such as compaction, pore size, bulk density, and resistance.

The mechanical stress is sensed using a pressure transducer which provides electrical signal for data logging [81]. The sensor can be used to assess soil conditions for replantation.

5.3.13 In Situ Soil Moisture Sensing Approaches

Because large amount of sensors deployment is not feasible in large forests, sensor-free approaches can be employed in forests. The resonant frequency based approaches and Di-Sense are two good candidates for this.

5.3.14 Radio Waves as Sensor: Propagation Based Sensing in Forests

In situ measurements and inversion approach can be used to measure the soil properties at higher depths with greater accuracy. In this paper, we have developed Di-Sense, an in situ, real-time soil moisture and permittivity estimation approach based on the wireless underground communications (WUC) in IOUT. For a transmitting antenna in the soil, the generated electromagnetic (EM) waves propagate through the soil, and are not only affected by the depth, distance, frequency, and soil moisture [84], but also depend on the properties of the soil [25]. Path loss of these attenuated waves received at the UG receiver can be used to deduce the proprieties of soil, and can also be used to estimate the soil moisture. Our approach to derive the soil moisture and relative permittivity is based on the path loss of the UG communications channel in IOUT. Path loss of transmitter-receiver (T-R) pair in WUC depends on distance, depth, and soil moisture. In Di-Sense, a transmitter antenna buried at a certain depth in soil transmits a wideband signal in frequency range of 100–500 MHz, which propagates through the UG channel. The received signal is measured at the receiver to determine the path loss. Di-Sense enables an IOUT system to communicate simultaneously besides real-time permittivity estimation and soil moisture sensing. A model has been developed to estimate the soil moisture and permittivity based on path loss using Di-Sense. The model has been validated through experiments in a software-defined radio (SDR) testbed and in an indoor testbed in different soils at different depths under different soil moisture levels. Relative permittivity results show a very good agreement with less than 8 % estimation error from ground truth measurements, semi-empirical Peplinski dielectric mixing model [74], and Topp model [91] (Fig. 5.7).

When EM wave communication is carried through the soil in IOUT, the propagation loss, due to the water molecules held in the soil medium, is a function of the real effective permittivity (dialectic constant) of soil. Therefore, propagation path loss of the soil direct path (between the transmitter-receiver (T-R) pair) can be used to

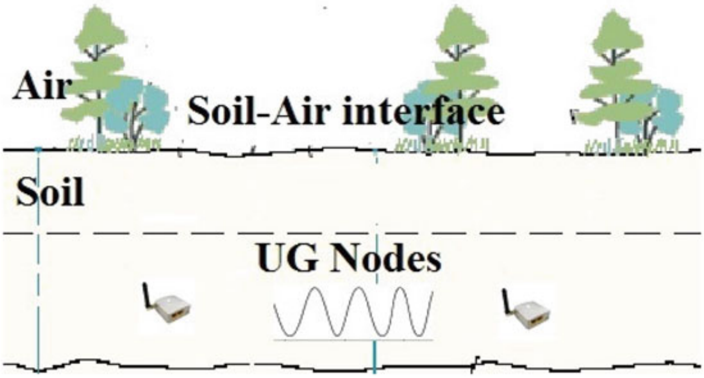

Fig. 5.7 Estimation of soil properties in forests using WUC

estimate the relative permittivity and soil moisture within 100 MHz-500 MHz range. To model soil permittivity, lowest path loss (LPL) across the whole frequency range is found by transmitting a known signal. The propagation path loss is determined by measuring the received signal. The transmitter transmits one signal using the narrow bandwidth at a time and frequency is increased sequentially in predefined step, Δf. Path loss is the ratio (expressed in decibel (dB)) of the transmitted power P_t to the power received P_r at the receiver. Path loss is determined as

$$PL = P_t - P_r = 10 \cdot \log 10(P_t/P_r) , \tag{5.1}$$

where PL is the system path loss, and includes the effects of transmitting and receiving antenna gains G_t, and G_r, respectively. Once the path loss is measured, the frequency of the lowest path loss is determined by

$$f_{min} = F(\min(PL(f))) , \tag{5.2}$$

where f_{min} is the frequency of the minimum pathloss. The f_{min} is not affected by distance between transmitter and receiver antennas because of the antennas gains. Therefore, system path loss PL is inclusive of the antenna gains. Since PL measurements are done in narrowband, noise effects is minimal. Next the soil factor, ϕ, is calculated as:

$$\phi_s = f_{min}/f_0 , \tag{5.3}$$

where f_0 is the resonant frequency of the antenna in the free space. Once the soil factor, ϕ_s, has been determined, the wavelength at the f_0 frequency is found

$$\lambda_0 = c/f_0 , \tag{5.4}$$

where c is the speed of light. Accordingly, relative permittivity of the soil is determined as:

$$\epsilon_r = \frac{1}{(\phi_s \times \lambda_0)^2} \,. \tag{5.5}$$

Permittivity Estimation Through Velocity of Wave Propagation in Soil Due to the inhomogeneity of the soil medium, permittivity of the soil varies along the communication link from point to point. This leads to variations in wavelength and phase velocity, as the wave propagates in soil. Therefore, permittivity of the soil can be measured from the velocity of wave propagation in soil. Power delay profile (PDP) are measured to get velocity of the wave propagation, that is determined from the known geometry layout of the testbed, by calculating the time that wave takes to reach at the receiver from transmitter. Once the velocity of the wave in soil, C_s, is determined relative permittivity in soil is calculated from the difference of transmission and arrival time of the direct component in the soil. Path of the direct component is completely through the soil. Accordingly, ϵ_r is determined as:

$$\epsilon_r = \left[C_s \times \frac{(\tau_{dr} - \tau_{dt})}{l} \right] , \tag{5.6}$$

where l is the distance between transmitter and receiver antennas, $\tau_{dr} - \tau_{dt}$ is travel time of the direct component in the soil, and C_s is the wave propagation velocity in soil. Due to different propagation velocities of the air and soil, direct wave is separate from the lateral wave which travels through the air along the soil–air interface, and has less attenuation as compared to the lateral wave [84]. In [86], an example power delay profile in the silt loam soil in the indoor testbed and attenuation in soil as a function of operation frequency are given.

5.3.15 *From Permittivity to Soil Moisture*

The relationship of the soil moisture and permittivity is independent of the soil texture, bulk density, and frequency [91]. Since, soil permittivity depends on the soil moisture only, soil water content can be determined from soil permittivity [50, 91].[1] Since dry soil has relative permittivity of 3, relative permittivity of the water is 80. Soil permittivity is calculated using (5.5) and (5.6), and accordingly, soil moisture is determined as [50, 91] (Fig. 5.8):

$$\text{VWC}\,(\%) = \frac{\epsilon_r - 3}{0.77} + 14.97. \tag{5.7}$$

[1] Although there is some error in soil moisture-permittivity relationship, and its dependence is also weak for mineral soils, it has been shown to work well in fine, and coarse textured soils [55].

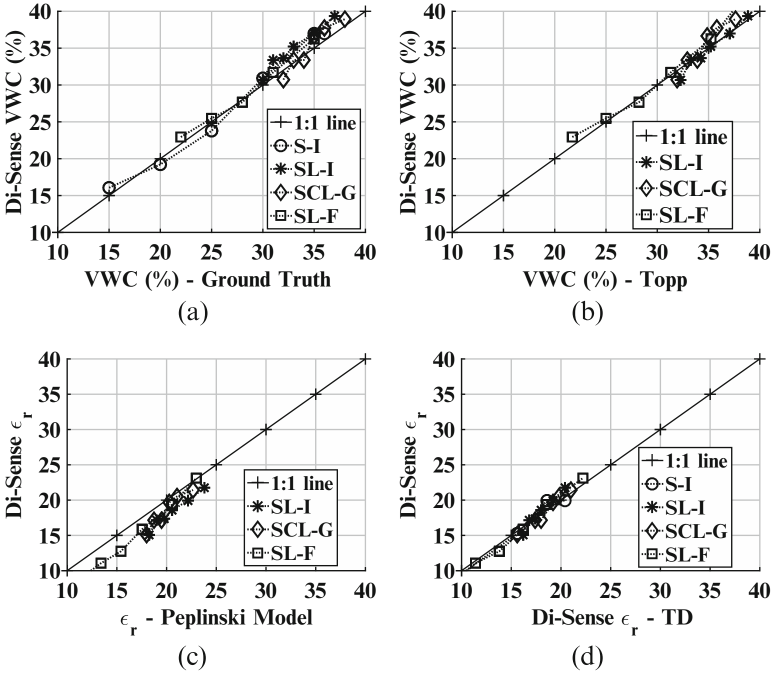

Fig. 5.8 (**a**) Di-Sense VWC compared with ground truth VWC measurements. (**b**) Di-Sense VWC compared with Topp model. (**c**) Di-Sense permittivity compared with Peplinski model. (**d**) Di-Sense permittivity by time-domain velocity of propagation comparison with Di-Sense path loss propagation permittivity method

5.3.16 Transfer Functions

It is worth noting that the results presented here are intended for soil moisture and permittivity estimation, but these can also be used for IOUT communication system design. Moreover, effects of changes in soil permittivity with change in depth are likely to be reduced at higher depths due to the fact that intensity of the reflected wave from soil–air interface is reduced at the deeper depths. For estimation purpose, following procedure would be used:

- Determine the lowest path loss frequency.
- Estimate soil permittivity using (5.5) and (5.6).
- Estimate soil moisture using (5.7).

Di-Sense transfer functions of the soil permittivity and soil moisture are shown in Fig. 5.9. Soil moisture and permittivity of soil medium can be determined using these graphs from measured values of IOUT propagation path loss. Di-Sense measurement technique is simple and easy to use, and no knowledge of type of radios, communication parameters, and antennas, being used in IOUT deployment, is

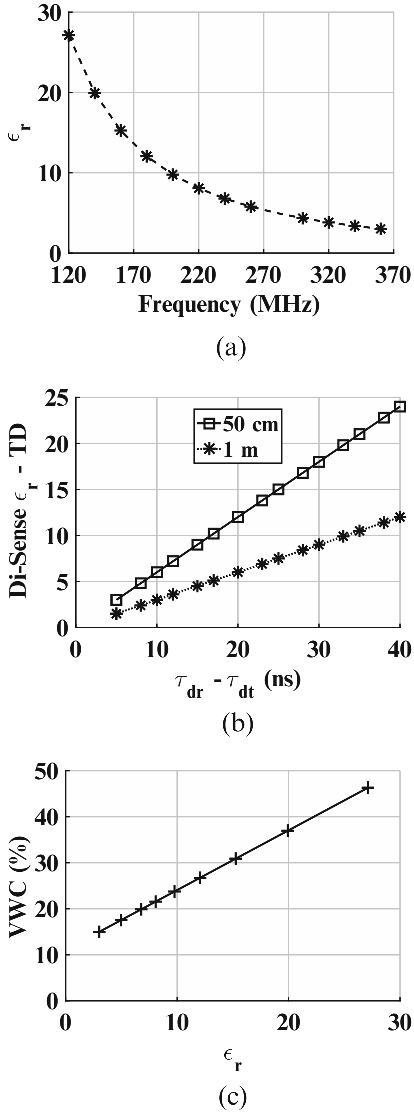

Fig. 5.9 Di-Sense transfer functions: (**a**) soil permittivity, (**b**) soil permittivity time-domain, (**c**) soil moisture

required, as long as propagation path loss can be measured accurately. Moreover, Di-Sense can also be used for different operation frequencies, f_0, because (5.3), (5.4), scale accordingly with respect to the operation frequency. Like other measurement based techniques, there are some limitations for which the Di-Sense method is applicable. The major limitation is that propagation path loss of the soil under test should be measured accurately. For the application of Di-Sense to the application scenarios, where higher accuracy is required, an empirical factor can be used to account for the specific soil properties and soil-water retention capability.

5.4 Modeling in Digital Forestry

The models in sustainable forest management also help to improve the forecasting, coupled with data obtained through sensing, satellite, and ground surveys. The data of spatial and temporal data combined with soil, organism, climate, and topography can be used to produce statistical models for futuristic ecosystems forecast at multiple scales. These different models are discussed in this section.

5.4.1 Habitat Modeling

The statistical habitat modeling provides useful insights about the impacts of future climate change on birds and trees habitats [70]. It has been developed based on the present habitat conditions and climate features. It has five different components:

- Climate Change Tree Atlas
- Climate Change Bird Atlas
- DISTRIB-BIRD: Modeling Potential Bird Habitats
- SHIFT: Modeling Potential Species Colonization
- DISTRIB: Modeling Potential Tree Habitats

5.4.2 Multi-Scale Machine-Learning Predictive Modeling

The deforestation is a major cause of biodiversity loss. A multi-scale machine-learning predictive modeling has been developed to model deforestation [26]. It provides the reliable estimates about the risk of future deforestation. The deforestation model predictions can be used to inform the sustainability and conservation practices in forest management.

5.4.3 Smoke Prediction Models

The operational smoke prediction systems (OSPS) is used to model fire-smoke related hazards. Accordingly, public health alerts can be issued using the sustainability forest IoT systems in WUI zones to avoid the hazardous impacts [82]. Many improvements are needed in smoke prediction modeling such as plume structure, fire dynamics, and weather. The advanced model can also incorporate sensing of fire, meteorology, and atmosphere to enhance the prediction capabilities.

5.4.4 Modeling Invasive Insects

The invasive insects pose a major problem to the forest health. A model has been developed to predict future invasions of various insects by considering their invasion routes and tracks [34]. It provides useful estimates about rates and number of invasions. Currently, this model is being employed to predict the invasion from Europe to the USA. It can be used to forecast and prioritize potential invasions and accordingly detection and identification mechanisms can be put in place in advance for efficient management and alerts. The Invasive Species Specialist Group (ISSG) network deals with invasive species [60]. Two other models are:

- Insect Flight Model. It is used to characterize cell based flight attributes [87].
- Insect Ride Model. A stochastic model to predict the insects ride by using external mediums [77].

5.4.5 Forest Disturbances Modeling

The forest disturbances affect the ability of forest to render important ecosystem services such as carbon sequestration [49, 83, 89]. In the carbon sequestration process the carbon dioxide is captured and stored by forests [68]. A model has been developed by using a satellite data of forest spanning over 25 year to model predict the various types of forest disturbances. This model has two different components:

- The first step uses random forest (RM) models to predict various types of disturbances such as fires, winds, stress, harvest, and conversion [103]. The non-parametric shape-restricted spline fitting algorithm and other spectral change metrics are employed as predictors along with other topographic and biophysical parameters.
- In the second stage, rule based spectral shape parameters are applied to first step output to identify temporal parameters of disturbances such as year.

This model gives highly accurate predictions of disturbances using the spectral metrics and other parameters. The applications of this model are in the area of disturbances mapping in different geographic zones around the globe.

5.4.6 Fire Behavior Modeling

The wildland fire behavior can be modeled using the fuel analysis, other parameters such as inherent vegetative fuels, weather, vegetation, atmosphere, and ignition patterns (e.g., BEHAVE-Plus). These models are divided into physical and empirical models. Currently, many model exists in literature for modeling of different types

of fuels. However, the models and fuel modeling science is lagging in terms of the accuracy and fuel complexity issues. The different fuels models are listed in the following [15]:

- Grass Fuel (GR) Type Model
- Grass-Shrub (GS) Fuel Type Model
- Shrub Fuel (SH) Type Models
- Timber-Understory (TU) Fuel Type Models
- Timber Litter (TL) Fuel Type Models
- Slash-Blowdown (SB) Fuel Type Models

The fire spread models are used to estimate spread of fire based on the type of fuel arrays. The test model (TSTMDL) is used for this purpose.

5.4.7 *Wildlife Habitat Suitability Modeling*

Wildlife habitat models are used to model the survival and reproduction of species in different environments. This model is used to assess the suitability of wild life habitat over long periods of times with variations in forest, tree structures, biomass, timber, and wood debris, and also considers harvesting regeneration processes. It can generate forecasts for large regions for periods of more than 100 years. It is useful to address wildlife conservation issues and challenges [20, 27].

5.4.8 *LANDIS*

The LANDIS is used to model forests (e.g., landscape, seed dispersal, succession, and disturbances). The grid cells are used to present various landscapes for per specie based representation. It has the ability to simulate different complex ecological scenarios and successions such as age-only, biomass, forest carbon, BFOLDS, PnET, and Net Ecosystem CN for different types of disturbances such as fire, wind, biological disturbance of insects and disease, harvest, and drought.

5.5 Forest Databases Integration with Forestry IoT

The important forest databases for integration into sustainable forest IoT are discussed in this section.

- Urban Tree Canopy Assessment. It is used to assess tree cover in urban environments and gives current and future canopy assessment. It can be used for planning purposes such a tree plantations. These decision can contribute to reduction and reduction in summer heat and air quality improvements.

- iTree. It is sustainability tool to assess the health of tress. It has global reach and provides robust information about the tree health. It can be used both for urban and rural settings for tree value education. It has three components: a database, a web-based mapping tool and model, and a mobile phone application.
- i-Tree PRESTO (PRoduct EStimation Tool Online). It is the enhanced version of iTree carbon storage estimation over large time periods.
- The Forest Inventory and Analysis (FIA) is a US forest databases. It contains enormous information about locations, trends, and status of the US forests. The various tools of FIA include DATIM, EVALIDator, Data Mart, fact sheets, and other reporting tools. It also provides detailed data about the endangered plant and animal species. Overall, FIA integration with forest IoT is useful to achieve sustainable forest management goals.
- Global Invasive Species Database (GISD). A database for effective prevention, mitigation, and management of invasive species.
- IUCN Red List of Threatened Species provides valuable information about facing the dangers of extinction.
- Spatial Hazard Events and Losses Database for the United States (SHELDUS) is used to assess forest losses caused by different hazardous events.
- NASA Disasters Mapping Portal. It has SRI ArcGIS-based web interface for to visualize disaster database in real-time. Other tools for this purpose are Hazards U.S. Multi-Hazard (HAZUS-MH) and Advanced Hydrologic Prediction Service (AHPS).
- The GuidosToolbox provides information about forest landscape and fragmentation at different scales scale.

5.6 International Organizations for Forests Sustainability

A list of organizations active in the area of forests sustainability is given below [42]:

- International Tropical Timber Organization (ITTO)
- Amazon Cooperation Treaty Organization (ACTO)
- Food and Agriculture Organization (FAO) Indicators Site
- FAO/ITTO Expert Consultation on Criteria and Indicators for Sustainable Forest Management
- International Union of Forest Research Organizations (IUFRO)
- Centre for International Forestry Research (CIFOR)
- European Forest Institute (EFI)
- United Nations Environment Programme/World Conservation Monitoring Centre (UNEP-WCMC)
- Forest Europe (formerly the Ministerial Conference on the Protection of Forests in Europe)
- Lepaterique Process of Central America on Criteria and Indicators for Sustainable Forest Management

- The Dry-Zone Africa Process on Criteria and Indicators for Sustainable Forest Management
- Regional Initiative for the Development and Implementation of National Level Criteria and Indicators for the Sustainable Management of Dry Forests in Asia
- The Near East Process on Criteria and Indicators for Sustainable Forest Management
- African Timber Organization
- The Tarapoto Proposal of Criteria and Indicators for Sustainability of the Amazon Forest
- International Conference on the Contribution of Criteria and Indicators for Sustainable Forest Management: The Way Forward (2003)
- Collaborative Partnership on Forests
- Community Indicators Consortium

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Chapter 6
Internet of Things in Sustainable Energy Systems

Abstract Our planet has abundant renewable and conventional energy resources but technological capability and capacity gaps coupled with water-energy needs limit the benefits of these resources to citizens. Through IoT technology solutions and state-of-the-art IoT sensing and communications approaches, the sustainable energy-related research and innovation can bring a revolution in this area. Moreover, by the leveraging current infrastructure, including renewable energy technologies, microgrids, and power-to-gas (P2G) hydrogen systems, the Internet of Things in sustainable energy systems can address challenges in energy security to the community, with a minimal trade-off to environment and culture. In this chapter, the IoT in sustainable energy systems approaches, methodologies, scenarios, and tools is presented with a detailed discussion of different sensing and communications techniques. This IoT approach in energy systems is envisioned to enhance the bidirectional interchange of network services in grid by using Internet of Things in grid that will result in enhanced system resilience, reliable data flow, and connectivity optimization. Moreover, the sustainable energy IoT research challenges and innovation opportunities are also discussed to address the complex energy needs of our community and promote a strong energy sector economy.

6.1 Introduction

The United Nations seventh sustainable development goal (SDG) is targeted to eliminating energy sector poverty [105]. The continuous and sustained efforts are required both at the strategic and governmental level to realize global access of energy [54, 122, 133]. Thus, the development of technologies and systems, coupled with policy making, governmental practices, and social transformation, is needed to enhance afford-ability and rapid global, regional, and local access of energy resources to the people [132, 134]. To ensure energy access at this scale, decentralized grid systems approach with resources distributed at the lower tiers will bring significant changes. The energy related SDGs are shown in the Fig. 6.1.

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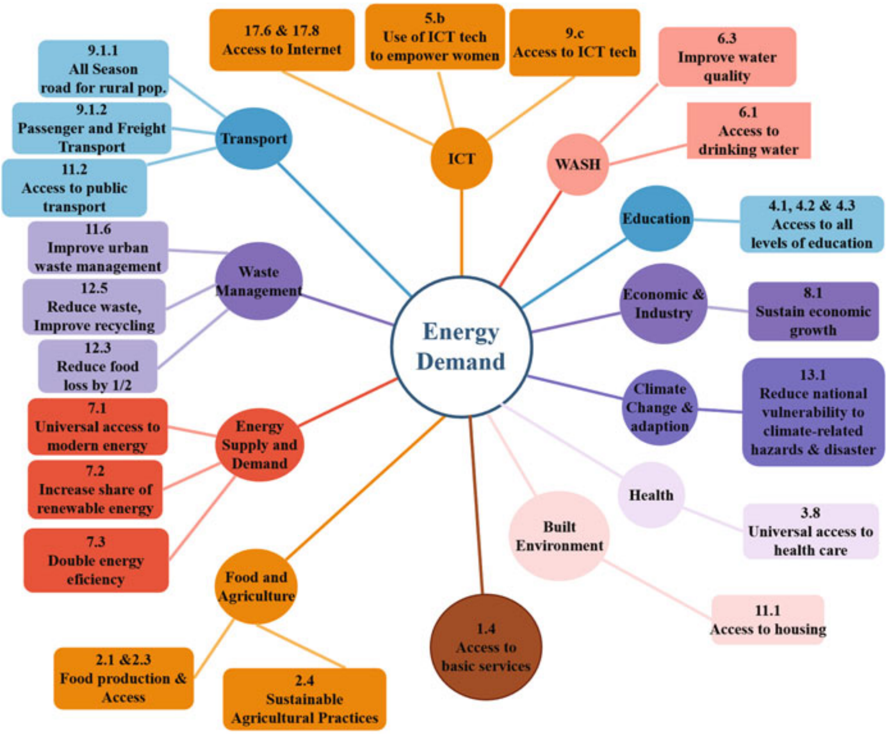

Fig. 6.1 The SDGs related to the energy [105]

It can be observed that energy demand has a strong connection with almost all of the UN sustainable development goals (SDGs). The energy access is highly correlated with the quality of life and plays a vital role in following sectors:

- The health and education sectors rely on dependable energy infrastructure [23, 119, 137]
- Provision of clean water needs energy [8, 54, 104]
- Energy drives the agricultural irrigation systems [121]
- Transportation sector cannot function without energy
- Household heating, cooling, cooking, and electric lighting require energy
- Industrial sector also relies on energy

6.1.1 Energy and Sustainability

The energy access [92] has the potential to reduce energy inequalities. The International Energy Agency (IEA) has defined the energy access as:

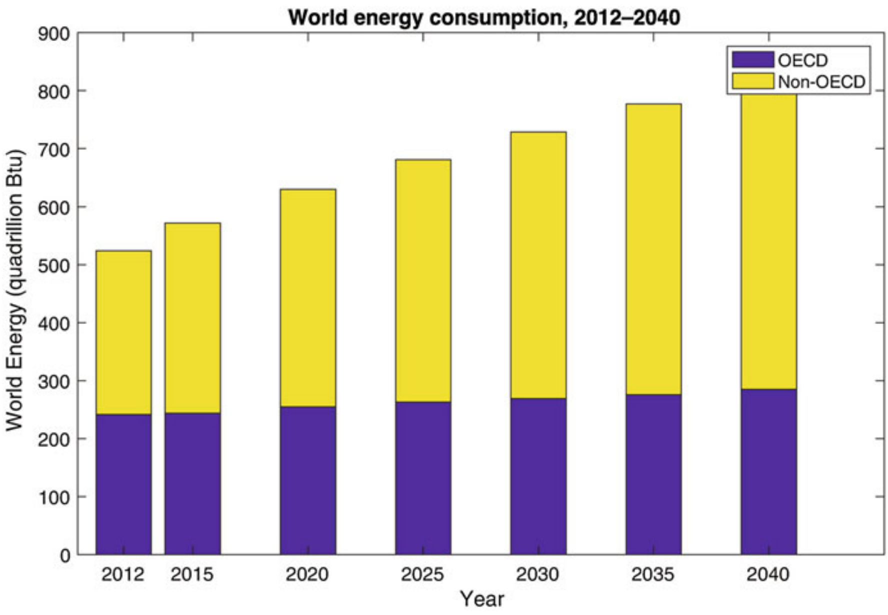

Fig. 6.2 The projected growth in energy demands of the world up to 2040 [88]

A household having reliable and affordable access to both clean cooking facilities, and to electricity, which is enough to supply a bundle of energy services initially, and then an increasing level of electricity over time to reach the regional average.

Currently, approximately more than one billion people have no access to electricity. The absence of energy access is impacting more to the poorest regions such as Sub-Saharan Africa (SSA) [19].

The increase in world population is predicted to outrun the present outlay of the supply of the novel energy access [88]. The projected growth in energy demands of the world up to year 2040 is shown in Fig. 6.2. The current expansion of the grid will play an important role to meet this demand; however, there is a strong need to discover new sources. The realization of inexpensive techniques for clean energy [47, 54, 104] is also pivotal for economic and agricultural growth, energy enfranchisement of the poor and to reduce the population mobility to the developed countries which is caused due to poverty lack of energy. The energy access is also useful to reduce gender inequality in developing countries where women spend their diurnal energy to collect firewood due to lack of adequate energy resources [92]. It also causes mental and physical health stress in girls and women [17, 74]. Therefore, in addition to being the fundamental requirement, the sustainable energy

access has tremendous socio-economic benefits to the community in terms of improving eradicating poverty and gender inequality. The UN's sustainable energy for all [103] program is flag-bearer for this vital cause.

Likewise, the advanced nations are also in need of continuous provision of energy. The energy is required for the functionality of businesses, high priority infrastructure, public safety, healthcare, and other industries. Moreover, potable water and wastewater treatment systems are dependents on energy access, where failure in one area can trigger cascading effects in urban utilities management. Therefore, achieving the energy resiliency is becoming the top priority of the city planners and managers [10, 23, 80, 93, 118, 119, 133, 136, 137].

6.1.2 Energy Related Challenges

As the modern advanced energy technologies are developing, there are emerging challenges that the future energy systems should address by using these advances [50, 128]. The current and future energy related challenges being faced by the community are discussed below. These challenges impact the capacity of power generation and also result in energy distribution disruptions.

- Current energy system depends heavily on water. However, with the variations in availability of water (short-term and droughts), novel techniques for energy production are needed [144].
- The high-voltage transmission lines lack security measures. These are also overloaded are being used afar their predetermined purpose. Moreover, transmission loss is also major issue which leads to power outages and blackouts [130].
- Many energy facilities are located in coastal zones due to high availability of water. But, rising sea levels and high tides, heavy downpours, and flooding from storm surges events are impacting coastal infrastructure and energy facilities and infrastructure [26, 62, 81, 106, 134]. The long duration energy outage in urban and industrial areas results in productivity loss that is also associated with business and economic loss.
- The extreme heat waves and summer temperatures are also causing high energy demands and corresponding increase in electricity usage. Due to peak loads the energy demands are projected to increase [135].
- The energy production and transportation infrastructure are also being impacted by extreme weather events [1]. Therefore, the frequency, duration, and intensity of these events cause energy disturbances which are occurring at different scales.
- One challenge associated with energy consumption is increase in greenhouse gas emissions [3, 138]. These emissions include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) [36]. These emissions are second highest following the majority emissions from the transportation sector.
- The energy consumption by information technology, mobile and computing devices is increasing [107].

- With more and more electric vehicles (EV) are being manufactured, the energy demand is increasing to fulfill EV needs [76].
- Other challenges related to energy infrastructure include a discrepancy between the demand and capabilities of energy systems, and the complex energy needs of industry and community [50].

6.2 The Sustainable Energy IoT

From the discourse of the energy and sustainability, it is evident that global energy access cannot be attained in the absence of technology adoption. Through application of technology the robust solutions for reliable low-cost energy access can be developed that can enhance the performance and operation of the current energy systems. Therefore, by using the next generation sensing and communication technologies, the need of affordable energy can be met for the community (see Fig. 6.3). The IoT technology that can efficiently provide the affordable energy services is necessary to address this basic human need of energy.

The IoT in sustainable energy systems is envisioned as the interconnection of the energy things in the entire paradigm grid system, services supply chains and human capital using state-of-the-art technologies with the ability to meet future needs and clean energy access challenges of the current century. This paradigm with its potential to produce next-generation energy systems is useful to connect various energy technologies and innovative solutions at the global scale. The sustainable energy IoT has the tremendous potential to attain sustainability and resiliency of prevailing energy infrastructure. It also has the ability to reduce future energy

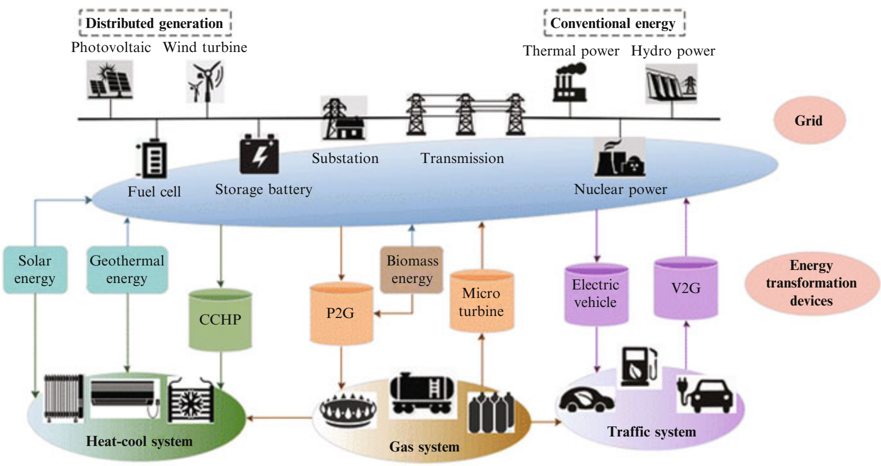

Fig. 6.3 An overview of the sustainable energy IoT

risks through development of secure, novel, and efficient energy infrastructure and technology. The IoT in sustainable energy systems enables various methods and pathways to global energy access through commissioning of clean and renewable energy methods with large-scale availability and scalability for sustainable provision of low-cost energy sources.

6.2.1 Sustainability Energy Things

The sustainable energy IoT carries a huge value for efficient energy value chain. Yet, the main value of the sustainable energy IoT lies in the smart grids, which is a significant achievement of the 21st century. The sustainable IOT paradigm with IoT autonomous and efficient management of the grid has a tremendous potential to bring benefits in consumption and generation. The sustainable energy IoT through its real-time monitoring of the renewable energy generation resources coupled with environmental monitoring can enhance the efficiency in the area of solar and wind power generation. Accordingly, these can be integrated into the grid to maximize the supply. It will also reduce dependence and pressure on less efficient, high demand, pollution causing fossil fuel based energy sources by using the distributed and low loss smart microgrids. The sustainability things are outlined in the following:

- Smart meters, net zero energy homes, green energy, and smart industry
- Generation, wind, solar, natural gas, water, renewables, and coal
- Transmission, phasor measurement unit, and transmission SCADA
- Distribution, smart and microgrid, and voltage control
- Billing, SAP, CRM, and work order management
- Customer, markets, retail energy provider, wholesale, and service provider
- Plant control, electric vehicles, and distributed intelligence
- Load, bulk, and outage management

6.3 Communication Technologies for Sustainable Energy IoT

The communications technologies are vital to provide connectivity in sustainable energy IoT. These form the integral part of the energy control systems are considered the backbone of the sensing and monitoring in energy systems. The most of the communication systems discussed in the first chapter of this book are being utilized in the energy sector. However, the advanced communication technologies pertaining to the sustainable energy IoT are discussed in this chapter. An overview of these technologies is provided in Fig. 6.4. These technologies are the driving force of the innovation in the energy sector and bring efficiency to all aspects of energy system.

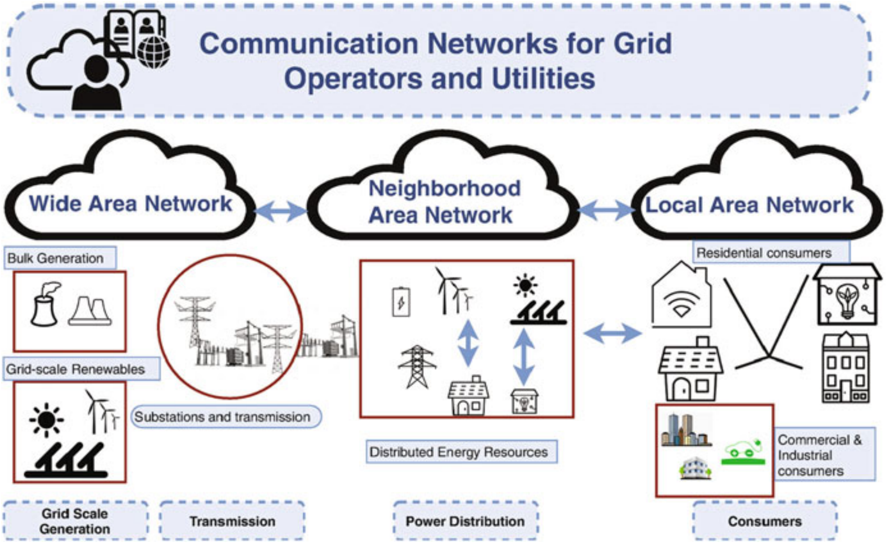

Fig. 6.4 Smart grid communications [38]

6.3.1 Wi-SUN

The Wi-SUN wireless smart utility (ubiquitous) network is a field and local area mesh networking standard supported by Wi-SUN Alliance [56]. It follows IEEE 802.15.4g and has its own physical and data link layer protocols. Its biggest advantage is that it can operate with multiple vendors.

6.3.2 Wide Area Monitoring Using SCADA

The supervisory control and data acquisition (SCADA) was developed in 20th century to collect power data from various geographical locations of the grid. It is main medium of communications between the substations and utility control stations. The SCADA has the capability to interface with large area monitoring systems and Internet, accordingly, robustness and efficiency has increased with this feature [6].

6.3.3 Neighborhood Area Networking

A neighborhood area network (NAN) [82] is an extension wireless LAN to multiple blocks of a neighborhood for the purpose of connecting to utility backbone network

and also to the Internet. A NAN can connect multiple smart meters to the grid. These networks are utilized for billing, energy load planning, and demand response on neighborhood basis. In these networks energy consumption is low and data rates are in the order of few kilobits per second. WiMAX standards can be used to extend the range of NAN and can provide data rates of up to 70 Mb/s. A design of the wireless NAN design for advanced metering infrastructure (AMI) in the smart grid with self-sustainable capability is presented in [141].

6.3.4 Power-Line Communications

In the power-line communication, the power cables are utilized as a channel for data transmission. Since, the electric energy companies already have a vast infrastructure to meet the needs of electric power supply, the advancements in the power-line communications will be beneficial for smart grid control and monitoring applications. These communications are divided into four types [112]:

- Ultra-narrow band (UNB) power-line communication (PLC): These communications are based on the use of ultra-low frequency (ULF) spectrum from 300 to 3000 Hz and also in 0.03 to 0.3 kHz.
- Narrowband power-line (NB) communication (PLC). These use the frequency band of 120 kHz using amplitude modulation. These also have low data rates.
- Quasi-band (QB) power-line communication (PLC). These communications operate in frequency spectrum of 1–10 MHz and provide high data rates of more than 2 Mbps. This is long-range communications approach for advanced metering infrastructure networks.
- Broadband (BB) power-line communication (PLC). These use frequency band of 1.7–250 MHz and support high level modulation schemes such as orthogonal frequency-division multiplexing (OFDM).

6.3.5 Other Communication Technologies for Grid

The advancement in power-line communications technology will also enable digital subscriber lines (DSL) over these power carriers. The DSL is able to achieve attain data rates of 1 to -100 Mb/s and classified into following types [99]:

- Asymmetric digital subscriber line (ADSL)
- Very-high-bit-rate digital subscriber line (VDSL)
- High-bit-rate digital subscriber lines (HDSL)

6.3.6 The Advanced Metering Infrastructure

The advanced metering infrastructure (AMI) consists of the following components [42]:

- Smart Meters. A two-way communication device which is used to measure the energy consumption of various appliances (e.g., electricity and gas heater). The smart meters are discussed in more details in the sensing section of this chapter.
- Home Area Networks (HAN). A communication and information network formed by the various appliances running within the home to support various distributed applications.
- Neighborhood Area Network (NAN). Network of multiple HANs for collecting and sending data to data concentrator.
- Telecommunications Network. A data communications network used to carry the metering data to control centers.
- Gateway. A device that collects data from the HAN's member (also from entire home as a whole) and transmits to next level.

6.4 Sensing in Sustainable Energy IoT

In this section, the sensing in various energy systems is presented. First, the sensing in nuclear power reactors is discussed.

6.4.1 Sensors on Nuclear Power Reactors

The nuclear power generation is a pivotal element of the sustainable energy IoT systems. Due to hazardous nature of nuclear environment to humans, reliable and autonomous sensors can reduce contamination hazards to humans. The sensors used in nuclear power reactors are discussed in the following section.

6.4.1.1 Vibration Sensing

The vibration sensing in nuclear power reactors is carried to monitor and avert environmental radiation discharge [9]. The vibration sensing also ensures the health and safety of plant equipment and employees for unhindered power generation. The nuclear power plant failures lead to negative financial and environmental impacts. The piezoelectric ceramic sensors give electrostatic charge signal based on the application of acceleration [9]. These sensors do not contain electronics based signal processing elements due to the high temperature nature on the environment. Accordingly, external signal processing is required for producing output. On the

hand, the use of smart sensors can mitigate this problem where signal processing, networking, and communication capabilities such as analog-to-digital conversions are done on board.

6.4.1.2 Temperature Sensing

The temperature sensing in nuclear power reactors is done both in control systems and also in safety and performance analysis systems [63]. For this purpose, chromel–alumel (thermocouples) and resistance based thermometers are used. Various types of temperature sensors are surface sensors and pool sensors. Currently, there is need of advancements in high temperature physical sensors technology for nuclear energy reactors such as in pebble bed reactors, where high drift is observed in thermocouples at high temperatures. Other temperature measurements approaches include [100]:

- Ultrasonic-guided wave thermometry. There are challenges in propagation of ultrasonic-guided wave [98]
- Johnson noise thermometry. It is susceptible to electromagnetic (EM) interference [18]
- Bragg thermometry. Susceptible to photo bleaching at high radiation [70]
- Optical sensors. The implementation of optical access ports to these sensors is challenging [24]

6.4.1.3 Pressure Sensors

The pressure sensors in nuclear plants are electro-mechanical instruments to determine pressure. These sensors can also measure the differential pressure, level, and flow [5]. These pressure sensors work by measuring the displacement of its mechanical parts which is changed to electronic form. There are also challenges in this conversion due to the high temperature. However, they suffer from leaks. The impulse line techniques suffer from salt contamination. The piezoelectric pressure sensors (Fig. 6.5) can also be utilized to sense dynamic pressure on short-term basis. Moreover, pressure sensors are also needed for higher reliability chloride salt and liquid fluoride environments. The polymer-derived ceramic materials are being investigated to fabricate pressure sensors, however, like temperature sensors, their interfacing to external circuits is challenging.

6.4.1.4 Liquid Level Measurement Sensors

The fluid level sensing is very important in reactors. The microwave techniques are used to sense levels of liquid salt. The other water level sensing approaches include ultrasonic using wave guides and impedance matching, pulsed neutron, neutron

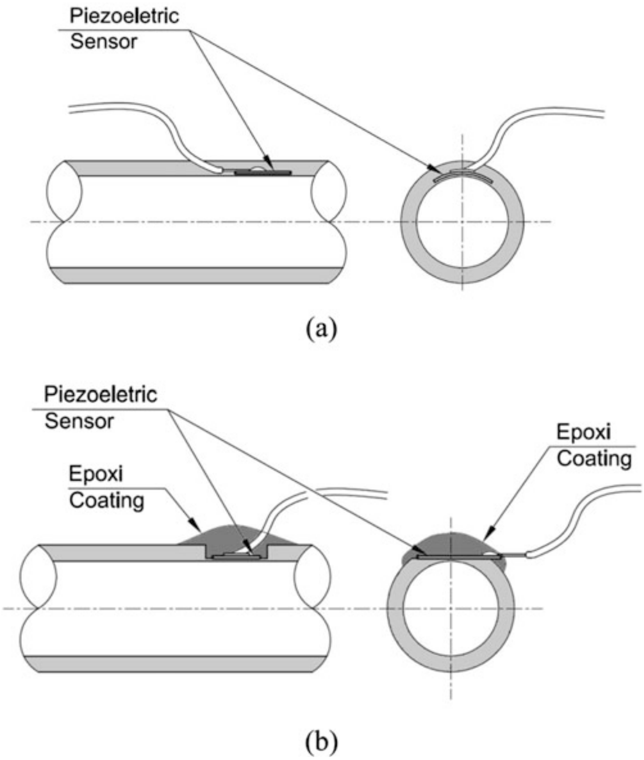

Fig. 6.5 Pipe with embedded piezoelectric sensors, (**a**) installed during fabrication of plastic pipes and (**b**) installed in fabricated pipes [72]

detectors, gamma thermometers, displacer float, conductivity, gamma horoscope, optical, and microwave [44]. However, these approaches are used as a short-term solution. The development of non-insertion (contact less) sodium level sensors is important for real-time monitoring.

6.4.1.5 Flow Sensors

The flow sensing can be either single phase or multi-phase is based on acoustic and ultrasonic methods [125]. The ultrasonic and acoustics are further divided into three types:

- Time-of-flight. In the time-of-flight sensing, 1 MHz frequency wave is transmitted to the pipe at an acute angle, propagates through the pipe, and is received at the other side of the pipe. The wave velocity in the pipe is impacted by the flow of liquid. Accordingly, the travel time of the wave is used for flow measurements.

- The Doppler flow meter. In this approach, the wave reflection is measured in contrast to the propagation (time-of-flight) measurements, where the shift in the reflected frequency in comparison to the transmission frequency is used to measure the flow [90].
- In contra-propagation transmission, the acoustics transmissions are alternated between the transmitter-receiver (TR) pairs installed on both sides of the pipes. The frequency difference is converted to the flow rate.

Based on the physical contact, these sensors can be categorized into two types:

- Intrusive sensors. These work inside the flow stream (e.g., head-type, segmental wedge, drag-type, and impedance sensors)
- Non-intrusive without penetration into the flow stream (e.g., acoustic, electromagnetic, microwave, optic, and nuclear)

The ultrasonic sensors are unable to sense at high salt temperatures and can also cause salt freezing to the heat absorption characteristics the waveguides. Therefore, for nuclear power plants, the development of ultrasonic sensors with capability to operate at higher temperatures (750 °C) is needed.

6.4.1.6 Corrosion Sensing

For the corrosion sensing, it is important to identify which corrosion causing processes. Currently, no techniques exist for in situ monitoring of corrosion and samples are analyzed off-line in laboratory environment. In this regard there is need of sensors technology in tritium sensing. Moreover, the water content monitoring is done to avert imprudent oxidation of reactor materials [29].

6.4.1.7 Radiation Sensors

The sensing of neutron flux is vital for nuclear reactor safety and operation and also for radiation monitoring [21]. For this purpose, the neutron flux and gamma flux sensors are used which can work in three different modes [61].

- Pulse mode during start-up
- Direct current ion chamber mode at full power.
- Variance mode for wide-range coverage

6.4.1.8 Water Coolant Chemistry

The water plays an important role in all power plants as the coolant. The production of energy uses water. Then impaired non-traditional water can be used as cooling with the advanced water recovery and reuse. The water chemistry sensing plays an important role in water quality and its cooling ability monitoring [94].

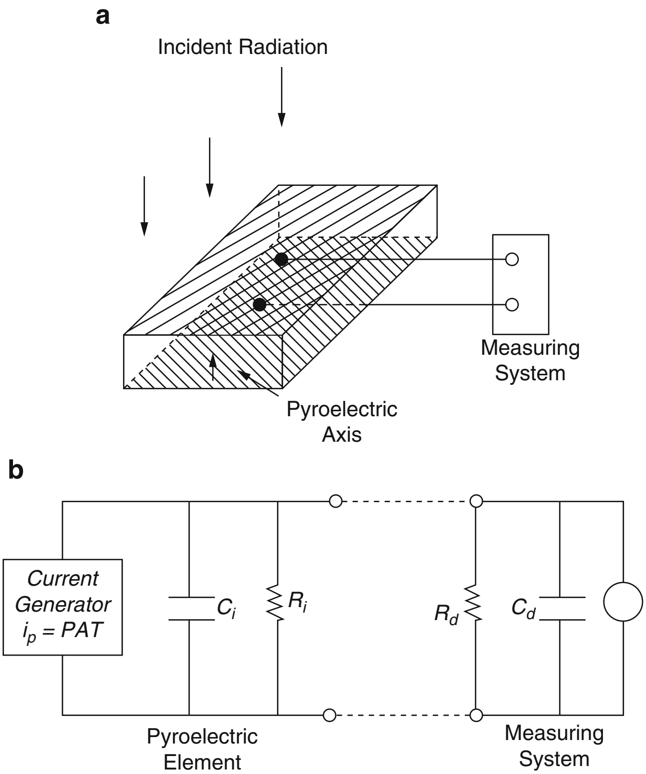

Fig. 6.6 (**a**) An experimental arrangement for infrared radiation detection and (**b**) the equivalent circuit [61]

6.4.2 Sensors for Coal-Fired Power Plants

The coal-fired power plants are another important component of the sustainable energy IoT systems due to their ability to provide flexible energy. In these plants, the monitoring is done to improve the efficiency of the combustion process and for sensors-based autonomous optimization. The coal-fired power plants sensing coupled with advanced stoichiometric control systems has the potential to improve the performance efficiency of these plants. These sensing approaches include coal, flame, carbon, and oxygen, and air flow sensing in various parts of the furnaces [126]. The sensors used in coal-fired power plants are discussed in the following section (Fig. 6.6).

6.4.2.1 Oxygen Sensing

The oxygen sensing is important for combustion monitoring in fossil fuel-fired power plants and is a good indicator of incomplete combustion [124]. The leftover oxygen is used to control the process by analyzing the use excess air in the combustion process. Accordingly, other firing rate and air intake are regulated. The process is optimized based on the reduction of oxygen set-point while minimizing incomplete combustion [52]. Two types of oxygen sensors are used in this application [131].

- The electrochemical sensors based on zirconia utilized air preheater and economizer. In these sensors, the oxygen ion-conducting (for temperature 300 °C and higher) solid catalytic platinum electrodes are used which have the ability to separate and absorb oxygen into electrons and ions [102].
- Since the strong magnetic field attracts oxygen, the paramagnetic sensors can be used for oxygen measurements. It is based on the usage of two nitrogen-filled glass in which oxygen is displaced resulting in suspension rotation which is sensed by photocells. This approach is less sensitive to other gases of the combustion process [60].

6.4.2.2 Carbon Monoxide Sensing

The carbon monoxide (CO) is another reliable indicator of the incomplete combustion process with optimum concentrations levels of less than 200 ppm. This is also used to adjust the oxygen set-point [97]. The CO sensors are discussed in the following:

- Electronic (Catalytic) Sensing. In this process, a combustion-prone platinum catalyst is used in which on oxidization of CO, the resistance of the sensor is increased. To avoid the catalyst poisoning, the ceramic substrate film thermistor is also used [58].
- Infrared (IR) Sensing. The sensors support both in situ measurements where IR sensor (a transmitter-receiver pair) can be installed along the flue ducts and also for extractive off-line sensing where gas samples has removed from the ducts [33]. For the first in situ approach, the recent advancement in the area of tunable diode lasers for the transmitters has improved the accuracy of these sensors in high temperature environments. In the second approach, one sensor is used which works by detecting the absorption frequency of CO.

6.4.2.3 Flame Sensing

The flame sensing in coal-fired power plants is crucial to the safety of the pulverized coal combustion. These sensors are installed on flame burners and work on optics

principles by measuring the infrared, visible, and ultraviolet light frequency of the flames. This data about the flame stoichiometry and temperature used to enhance the combustion process [145].

6.4.2.4 Coal and Air Flow Sensing

The monitoring of the air flow in pulverizer mills and furnace is also used for combustion process optimization [16]. For this purpose, the flow meters are used to assess the pressure reduction when passing through a narrow section of the pipe. The pitot tubes are also employed for pressure measurements.

The coal flow is also sensed by using feeding rate of the coal (gravimetric) to the pulverizer mills that is dependent on the firing rate of boiler and load demand on the plant. The electrostatic approach is also used for this purpose where two electrodes are utilized to sense the charge associated with the flowing coal between two points along the length of coal flow. According, the time of travel based on the coal velocity is used to sense flow.

6.4.2.5 Sensing of Carbon Content in Ash

The carbon ash content is also a good indicator of the combustion process efficiency [34]. The content of less than 20% is generally maintained. The carbon content measurements are generally performed using microwave techniques. Due to high permittivity of the carbon, the EM waves are absorbed by the carbon depending on the dielectric constant. Accordingly, the resonant frequency changes are detected by using the resonance cavity sensors.

6.4.2.6 Gases and Temperature Sensing

The gas sensing [115] at single location is generally not representative of the gas concentration. Hence, arrays of gas (linear and planar) sensors are employed for this purpose to get overall picture. The tunable diode laser absorption spectroscopy is another development for sensing of the flue gas concentrations with very high accuracy. The furnace exit gas temperature sensing is also important for furnace control. The temperature sensing can be done by using some of the approaches discussed in the nuclear reactors section. The nitrogen oxide sensing is also carried out to sense nitrogen oxides in the plant.

6.4.3 Transmission System Sensors

The sensing of the grid transmission systems is vital due to many factors [87]. The smart grid sensing technologies are shown in the Fig. 6.7. These sensing

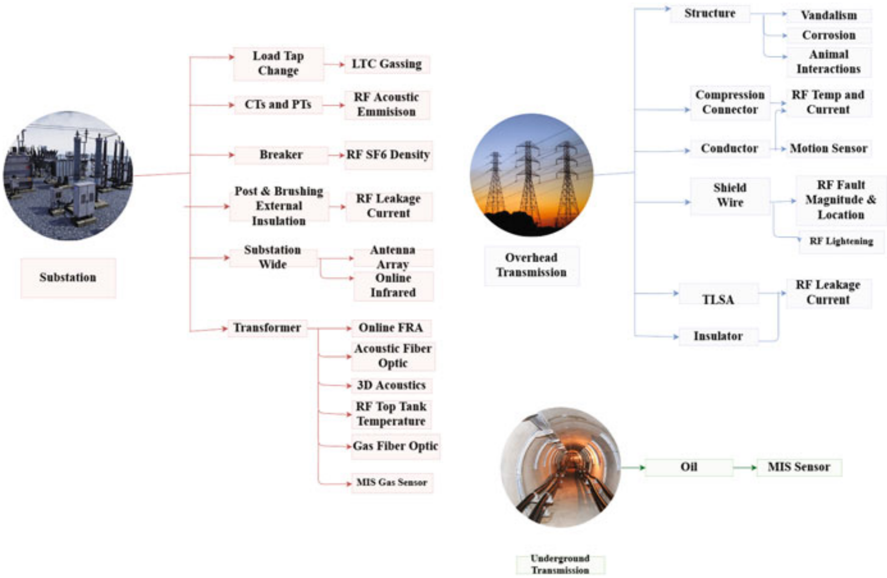

Fig. 6.7 The smart grid sensing technologies [87]

technologies are either fully developed are still in under development. Their applications are discussed in the following:

6.4.3.1 Substation Sensing Methods

The substation sensing methods are discussed below:

- Substation Discharge Monitoring: It is important to monitor potential discharge at substations to avoid catastrophic failures [140]. For this purpose, the antenna arrays are being used to sense, locate, and identify components that are causing discharge. Moreover, the 3D acoustic emissions techniques are also being used for discharge sensing in transformers. The 3D acoustics is also used to sense of bubbling sources and gas sources.
- Video Imaging: In this approach the IR tomographic cameras are used to produce video thermal images of substation components.
- Metal Insulated Semiconducting (MIS) Gas in Oil Sensor: In this approach, an inexpensive hydrogen sensor is used to measure the H_2 and C_2H_2 in transformers head-space and oil. The MIS gas sensor is manufactured on a chip [111]. This sensing approach is also used to sense hydrogen and potential acetylene in cable oil.
- Fiber Optic Based sensing. There are two types of fiber optic based sensing: acoustic and gas. In acoustic, the stress areas of the transformers are monitored for discharge using fiber optics cable. In the second approach, the gas presence

at the tip of the fiber optics is used to identify early failures and degradation in high risk areas [32].

- Frequency Domain Analysis: It works on the principle of frequency domain analysis of the transformers. In FDR approach, the variations in frequency response measurements are used to identify the configuration changes of the transformers. These measurements are done contentiously using natural transients [66].
- Sensing Gas in System Load Tap Changer (LTC): This sensing approach is capable of measuring the LTC gas ratios without the requirement of individual gas measurements [57].
- Radio Frequency. The RF based sensing approaches are used to sense leakages of the current levels to inform insulation washing and flash-over for various types of insulations [114]. These are also able to perform wireless/remote identification of high risk components (e.g., acoustics based internal discharge, current, jaw temperature of disconnect, and density of sulfur hexafluoride). The time and magnitudes of fault currents flowing in the shield wires are utilised for this purpose.

6.4.3.2 Overhead Line Sensing

The overhead line sensing approaches are discussed in the following:

- In overhead transmission, the current and temperature sensing approaches are utilized to sense temperature of connectors, current magnitudes, compression of conductor such as dead ends and splices. Accordingly, a histogram is created to assess loss and to identify high stress components. These sensors are capable of energy harvesting from the abundant magnetic field prevailing in the line environment [71].
- Similar to the substation environment, the overhead insulator leakage and associated currents are measured using RF approaches. The time and current magnitude of the current flowing are also measured in shield wire to identify the exact location of faults. The same measurements are also done for the lighting current distributions [30].
- The surge sensor is used to measure and log surges and total charge detected [40].
- The transmission structure sensing is done using sensing of the environment data and image processing for decision support systems. Accordingly, different incidents such as unknown outage and avian activities can be detected in real-time [65].

6.4.4 Smart Meters

The smart meter is also a type of sensors in sustainable energy IoT. The smart meters are the fundamental components of the advanced metering infrastructure (AMI). These connect customers and service providers via different types of communica-

tions links [129]. The smart meters are also used for monitoring of duplex power flow. Accordingly, the dynamic billing, load monitoring, and remote functionality are enabled through the use of smart meters.

6.4.5 Wind and Solar Sensing

The reliable integration of solar [68, 73] and wind energy [10, 11, 15] resources in the sustainable energy IoT requires real-time sensing of these environmental parameters for the efficient energy generation process [116]. These environmental sensing is done for solar irradiance and wind speed. This type of weather-related variables sensing in sustainable energy systems has the tremendous potential to bring more multitude of energy sources to the power systems.

6.5 The Case Studies of Sustainable Energy IoT Technologies

In this section, the sustainability IoT case studies are discussed in great details.

6.5.1 Electric Vehicle Energy Internet

The basic idea of electric vehicle (EV) energy Internet is to transmit energy from one place to another [35, 142]. The EV transmits, stores, and distributes energy from renewable energy sources (e.g., solar, wind) to the places where needed such as charging stations and houses. EVs are equipped with the batteries and together can form a large network of distributed energy storage system, e.g., if all light vehicles in USA become EVs then the entire power generated by them will be 24 times higher than the entire electric generation grid. In Fig. 6.8, a schematic of EV energy Internet is shown. It divides the EV into two layers [142]. The lower layer is the transportation network of EV architecture. It consists of energy generation from renewable resources, energy transportation from EVs and energy substations, and consumers. The EV, after charging at renewable energy source, travels to a charging station and discharges at charging station. Accordingly, other EV picks up the energy from that substation and move to the next point.

6.5.2 Combined Cooling Heating and Power System

The combined cooling heating and power system (CCHP) is a distributed generation system that can provide heating and cooling simultaneously. When compared with

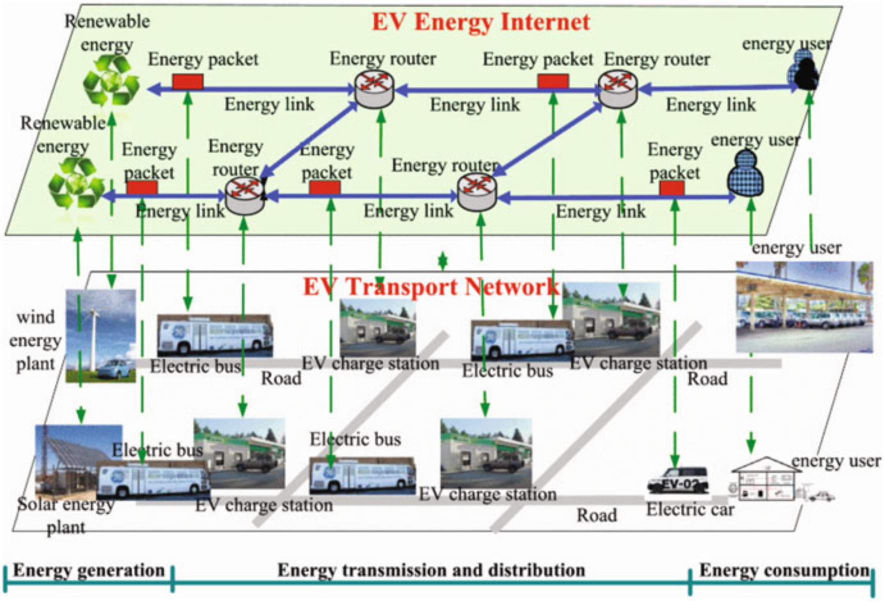

Fig. 6.8 A schematic of EV energy Internet [142]

the traditional alternative, such as separate cooling and heating system, the fuel economy and system efficiency of CCHP are higher. It consists of power generation, heating, and cooling. The CCHP can balance the production and load requirement of electricity, heating, and cooling increasing the overall efficiency from 40% to 70–90%. Moreover, the emission reduction is an added advantage of CCHP system [22].

6.5.3 Power-to-Gas (P2G) Energy Internet

Energy markets all over the world are now focusing shift from fossil fuel-based power generation to renewable energy-based generation. EU has proposed that a target of 20% renewable energy will be achieved, in their mix of energy systems by 2020. This is because of the low emission rate and environmental friendly nature of renewable sources. However, as discussed in the previous sections, the production pattern of renewable sources such as wind and solar is very unpredictable and varying. In addition to unpredictable generation capacity, they may also cause fluctuations in grid. Although, renewable energy has all these challenges, however, they are still considered as future of the energy sources.

One solution to the above problem is to store a large amount of energy when demand is less than the supply and using that stored energy when the demand

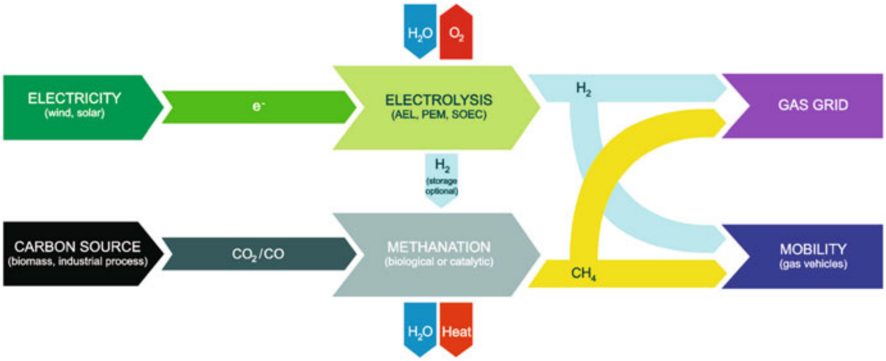

Fig. 6.9 The power-to-gas process chain [48]

increases the supply. This flexibility in the system can be achieved by power-to-gas (P2G or PtG) [48]. As shown in the Fig. 6.9, the P2G is a process of converting water to hydrogen via electrolysis and then conversion to methane. The P2G is a very flexible option for long-term storage of energy produced by renewable energy source-based plant. It adds flexibility to the current energy based system. The P2G offers three benefits in terms of flexibility: (1) time, (2) location, and (3) end-use. Apart from being a long-term energy storage technology, the P2G is also used to balance electric and gas networks [83].

6.5.3.1 Water Electrolysis

The key step of P2G technology is conversion of energy into hydrogen via water electrolysis. In water electrolysis, electric energy is converted into a chemical energy [127]. The conversion process is carried out by electrolyzer. Electrolyzers consist of (1) electrodes, (2) electrolyte, and (3) a diaphragm. Electrodes split the water into hydrogen and oxygen upon supply of electricity. Electrolyte is used to conduct ions and diaphragm act as an isolator to prevent evolving gas streams from flammable mixture. Electrolyzers can be classified into different types based on the type of electrolyte being used. In the following sections, various technical aspects and characteristics of these electrolysis are discussed.

6.5.3.2 Alkaline Electrolysis

Alkaline electrolysis is considered as one of the mature electrolysis processes and it is present in the industry for a decade. They use aqueous alkaline solutions, e.g., KOH or NaOH, as an electrolyte. The highly perforated steel electrodes are separated by insulated diaphragm. It works under atmospherically under high pressure. The atmospheric alkaline electrolysis has higher efficiency than the elevated

pressurized one [64]. However, advantage of pressurized alkaline electrolysis is that it produces compressed hydrogen with low amount of input energy. Some of the drawbacks associated with the alkaline electrolyzers are:

- Minimal load capacity of 20–40% PN
- Long start time ranging from 10 min to hr depending upon the purity of the gas
- Long restart times. It takes typically 30–60 min before it can be started again

6.5.3.3 Proton Exchange Membrane (PEM) Electrolysis

It was developed by general electric (GE) in 1966 and was introduced to the market in 1978. It uses polymer membrane as an electrolyte [43]. The nature noble metal is used as a catalyst due to its acidic property. Some of the advantages of PEM include faster cold start, high flexibility, and better coupling with the dynamic systems. However, usage of noble metal as a catalyst makes it a highly expensive option and the life span of a PEM-based system is shorter than alkaline-based systems.

6.5.3.4 Methanation

Hydrogen and carbon dioxide are further processed via Sabatier reaction to produce renewable power methane [127]. The process uses nickel and ruthenium based catalyst. It operates under the temperature of 250–400 °C and pressure of 1–80 bar. Due to exothermic nature of the process, highest conversion is attained at low temperatures leading to low kinetics. Almost 17% of the hydrogen energy is released as a heat limiting the maximum achievable efficiency to 83% provided that no extra heat energy is used.

6.5.3.5 Challenges

P2G is in the developmental stages. Research in P2G is going in two directions. First direction is the improvement of modules like electrolyzer and methanation [127]. The second is the improvement of P2G in systems. The main challenges to explore are:

- Establishment of proper framework for P2G as a system balancing technology
- Lack of precise data results in uncertainty in modeling of P2G technology which makes it impossible to get reliable results
- Lack of case studies to analyze the economic and social impact of P2G technology
- Design of smart management system for P2G

6.5.3.6 P2G Opportunities in Sustainable Energy IoT

The P2G opportunities in sustainable energy IoT are discussed below [2].

Sustainable Energy Systems Sustainable energy systems are the ones which remain operational even during the rapid changes in demand and supply. The response time of P2G technology is fast (typically takes from seconds to minutes). This adds up to the flexibility of energy systems. It also increases the flexibility of the energy systems by significant share of the renewable energy sources.

Reducing Emissions in Energy Sectors The carbon capture and utilization (CCU) technologies are used all over the world to capture harmful gas before it emits to the atmosphere. The CCUs are developed to reduce the adverse environmental effects. Carbon dioxide is necessary for the production of hydrocarbons. It is a very good opportunity to use the CO_2 recovered from CCUs units. Accordingly, there is a possibility of using captured CO_2 for the production of methane via P2G [12].

Congestion Management The high production from the large renewable power plants connected to an electric system can cause congestion in the power transmission lines. Therefore, to avoid the suppression of energy production, it is necessary to install P2G energy storage system in close vicinity to the power plants.

6.5.4 Sustainability and Net Zero Energy Buildings

The sustainable development in energy sector requires the new types of building designs with renewable integration for high energy efficiency [39, 49, 75, 85, 86]. In this regard, the net zero energy buildings (NZEB) is an emerging concept that is being conceived and implemented as a solution to minimize consumption of energy in buildings. There are different technologies for NZEB design [7]. The four different types of net zero energy buildings are shown in Fig. 6.10. These buildings have different sources of renewable energy either on premises in the vicinity to meet energy needs. The NZEBs are also connected to electric grid as well for energy demand in case of low output of renewable sources. However, in favorable conditions for renewable energy (such as solar and wind), the NZEBs are not only able to meet their own needs but also dispatch the excess supply to the grid. Therefore, it balances the demand and supply in terms of the energy consumption.

The net zero energy buildings also has the tremendous potential for environmental sustainability and economic benefits through their net-zero carbon emissions [110]. Because, mostly in buildings gas and other petroleum energy resources are used in fossil fuel boilers and furnaces for heating needs. When replaced with renewable sources (such as air, solar, and water based pump solutions), the carbon footprint is decreased. Moreover, through sustainable IoT's real-time monitoring, sensing, and visualization, the autonomous control can be implemented based on the dynamic needs and conditions of the environment.

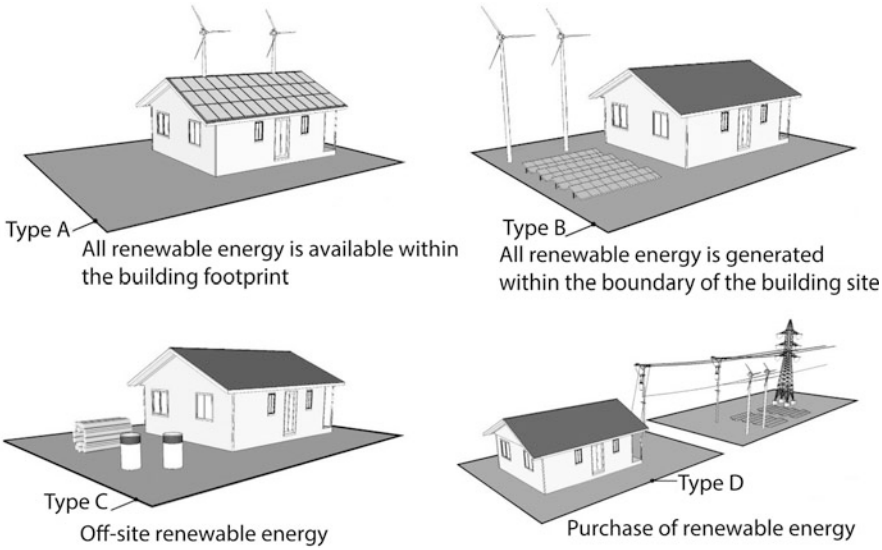

Fig. 6.10 The four different types of net zero energy buildings [39]. Type A: All renewable energy is available within the building footprint. Type B: All renewable energy is generated within the boundary of the building site. Type C: Off-site renewable energy (for example, wood pellets, biodiesel, or ethanol) is used to generate energy. Type D: Purchase the renewable energy which is generated off site

6.5.5 Energy Supply Chain Management

The sustainability energy IoT has many benefits in the areas of energy supply chain management, infrastructure security, and logistics. For example, in fuel depot monitoring applications, various types of sensors provide useful information [13], such as:

- Sensing of temperatures, tank fluid levels, and flow rates is done for accurate and low-cost monitoring
- The leakage can be detected in real-time using water, soil, and air sensing
- The control, usage inventory, and ordering can be achieved through autonomous operation in online or remote fashion, accordingly, the exposure to food related hazards is minimized
- The motion sensors and cameras things connected to the system enable enhanced infrastructure security
- Early detection of failures can be done by sensing of corrosion and cracking in high risk areas

6.6 Sustainability in Energy Generation

With the growth in world population, the fossil fuels are depleting rapidly. Accordingly, due to increased usage and high stress on fossil fuel and other oil based energy resources for transportation and power generation, these is an urgent need of mining energy from renewable sources [25, 55, 78, 79] and exploration of new resources. In this section, the sustainable energy generation from different sources is discussed.

6.6.1 Hydrogen

The hydrogen based energy preproduction is also a good alternative to gas and electricity [113]. It can be produced by using electrolysis, reformation, and gasification. However, there is need of carbon storage facilities for efficient sustainable hydrogen production such as the hydrogen fuel cells. By using polymer electrolyte membrane fuel cell (PEMFC), the hydrogen can also be used to produce electric power with no emissions. The electrohydrogenesis is another biohydrogen production method. It can be considered as an alternative to combustion fossil fuel engine in electric cars.

6.6.2 Biobutanol

The biofuel availability in transportation sector is currently dominated by bioethanol and biodiesel [67]. However, the biobutanol is being considered due to its superior properties as compared to the bioethanol. It can be produced through the fermentation of butanol, acetone, and ethanol [139]. Fermentation and the latest research achievements in feedstock and process development are briefly pointed out. The new ethanol to butanol catalytic approaches are being considered as an alternative to fermentation.

6.6.3 Bioethanol

The bioethanol is alternative to petrol and is obtained through biological techniques. The development of engines with the capability to solely operate on ethanol is bringing innovations in bioethanol production [20]. The steps in production technologies are [51]:

- Microbial fermentation of sugars to ethanol
- Pre-treatment of carbohydrate polymers
- Separation of ethanol by distillation
- Dehydration to fuel-level bioethanol

6.6.4 Biodiesel

The biodiesel is a sustainable and renewable alternative to petroleums. It is produced by using transforming the waste microalgae and cooking oils to biodiesel by using different methods which including lipase preparations [77, 109]. The enzymatic biodiesel has many environmental benefits as compared to the chemical catalytic process. Other state-of-the-art production technologies include metabolic and genetic engineering and biological synthesizes.

6.6.5 Microbial Electricity

The wastewater can be used to produce electricity by using bio-electro-chemical equipment known as the microbial fuel cells (MFC). The electro-active bacterias in the vicinity of electrode transfer electrons during their metabolic process, which are used to produce electricity. The success of this approach is very important for sustainable energy production [91, 117].

6.6.6 Biomass

The biomass [3, 27, 41, 95] (e.g., forest residues, bales and chopped straw, and pellets) has attracted a lot of research focus due to its applications in various energy areas such as power, heat, and in production of biofuels and bioenergy [28, 53, 96, 101, 108, 120]. Different approaches are discussed in the following:

- The biomass gasification is a combustion-free thermo-chemical approach to convert the biomass to fuels. The solid wastes and feedstocks can be converted into energy by using this approach. There is need of innovative development in the area of gasification [69, 113].
- The anaerobic digestion (AD) is another emerging technology to produce renewable energy from solid organic wastes and biomass. It also produces phosphorous, nitrogen, and micro-nutrients byproducts that can be used as fertilizer for soils in agriculture [89].
- Moreover, the synthesis gas (syngas) can be produced from organic biomass by using the supercritical water gasification approach. This results in tar and char formations and currently has low gasification efficiency [14].
- Furthermore, the biomass is also used as co-fired along with coal in various forms. When pelletized, it achieved high energy efficiency in coal combustion. The dendromass (a biomass of roots) is also another renewable energy source from short rotation woody crops [46].

- The woody biomass is also used to produce activated carbon through thermal means that can be utilized for waste treatment and gas purification [143].
- The perennial grasses are also used for energy production. It is species of giant miscanthus, switchgrass, and reed canary grass [59].
- The microalgal biomass and oil crops are other important sources [37].

Other major renewable energy sources are outlined in the following:

- Nuclear. It is a reliable source of energy generation. Currently, the second and third generation reactors are in user. However, the research is on ongoing in fourth generation reactors [31].
- Ocean. Ocean tides and waves are also a good source of renewable power generation [123].
- Hydropower. The run of river, regular storage, and pumped storage are some of the examples of the hydropower plants [84].
- Geothermal. The sustainable energy can also be produced from low temperature heat reservoirs and sources [45].
- Wind. Many configurations of wind energy conversion systems (WECS) are in commercial use [10, 11, 15].
- Solar. The solar photovoltaic (PV) technology is highly scalable and is being used from milliwatt to gigawatt scale production [68, 73]. It is also being used in off-grid solar configurations [4].

6.7 Sustainability IoT Systems and Databases

The sustainability IoT systems and databases are presented in this section.

- Solar Roadmap. A community level solar information database to increase adoption of solar energy.
- BioEnergy Atlas. It is interactive mapping system for BioFuels BioPower.
- RETScreen. A Canadian clean energy software.
- Planning Framework for a Climate-Resilient Economy. A community level framework for climate resiliency and economic vulnerability identification.
- Geothermal Prospector. A tool to map geothermal power resources.
- US Energy Information Administration (EIA) energy mapping system is an U.S. energy infrastructure database.
- The Bioenergy Knowledge Discovery Framework (KDF) contains database for bioenergy analysis, research, and decision-making
- HydroSource. It is an integrated data set for water, energy, and ecosystem sustainability. It has geospatial data sets for hydro-electricity production and water management.
- U.S. Electric System Operating Data. A tool for visualization and analysis of hourly USA and regional electricity demand.

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Chapter 7
Internet of Things for Sustainable Human Health

Abstract The sustainable health IoT has the strong potential to bring tremendous improvements in human health and well-being through sensing, and monitoring of health impacts across the whole spectrum of climate change. The sustainable health IoT enables development of a systems approach in the area of human health and ecosystem. It allows integration of broader health sub-areas in a bigger archetype for improving sustainability in health in the realm of social, economic, and environmental sectors. This integration provides a powerful health IoT framework for sustainable health and community goals in the wake of changing climate. In this chapter, a detailed description of climate-related health impacts on human health is provided. The sensing, communications, and monitoring technologies are discussed. The impact of key environmental and human health factors on the development of new IoT technologies also analyzed.

7.1 Introduction

The sustainable development goals (SDGs) are a set of goals established by United Nations (UN) following the millennium development goals (MDG), in 2015 by 193 UN member nations to address health, climate, and environmental issues being faced by the humanity [69]. These SDGs have laid a special focus on sustainable approach for future health and present a vital scope to foster the appropriate environment for an improved human health by the way of sustainable society. Thereof, four vital issues are identified [63].

- Necessity of systems approach for sustainable health
- Importance of health society for community's prosperity
- Assessment of climate change impacts and additional perils to sustainable health and to provide expeditious health benefits
- Development of indicators, models, and metrics to observe and project different health impacts in terms of threats and risks

To achieve SDGs objectives, a new systems paradigm is required across the various prongs of sustainable development (e.g., world, mankind, and well-being).

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For this purpose, integration of sensing, communications, monitoring, and decision support systems is required for sustainable health IoT paradigm, under the guidelines of United Nations and World Health Organization.

7.1.1 Sustainable Health IoT

The sustainable health IoT enables development of a systems approach in the area of human health and ecosystem. It allows integration of broader health sub-areas in a bigger archetype for improving sustainability in health in the realm of social, economic, and environmental sectors. This integration provides a powerful health IoT framework to sustainable health and community goals in the wake of changing climate [31, 40, 87, 89]. The other climate mitigation approaches using the IoT paradigms also carry many health benefits such as health community is achieved via sensing and corresponding improvements in air quality, green urban environment, and reduction in flooding [14, 123, 146, 150]. The IoT paradigm also enables many health benefits of adaption and mitigation while providing insights climate-related health impacts [47, 86]. The climate change impact on human health is shown in Fig. 7.1 [153]. Because of this factor, either the current health problems become worse or new unparalleled health issues are generated.

The sustainable health IoT has the strong potential to bring tremendous improvements in human health and well-being through sensing, monitoring of health impacts across the whole spectrum of climate change. It is envisioned to provide health and environmental data that can be utilized to characterize the impacts of climate change on human health [47], which in turn enables identification, projection, and effective response to human health related threats. The impact of climate change on human health is discussed in the following section.

7.1.2 Climate Change and Human Health

A significant threat is being faced by the humanity in health related issues because of the climate change [15, 25]. The impact of weather and climate on human health is very significant and diverse. This exposure to climate induced health issues is impacting the community and people in different ways. There are many ways (e.g., environmental emissions, ozone exposure, water and air quality, temperature, and weather) in which human health is being impacted by the climate change [46, 50, 101, 109, 126, 160]. Particularly, the increasing concentrations of the carbon dioxide and rising temperatures, and their relation with variations in plants, flower production, and allergenic initiating time has led to increased production of the allergens [73]. The rise in emissions is also cause of rising temperatures and sea levels, variations in precipitation patterns, increase in extreme weather pattern.

	Climate Driver	Exposure	Health Outcome	Impact
Extreme Heat	More frequent, severe, prolonged heat events	Elevated temperatures	Heat-related death and illness	Rising temperatures will lead to an increase in heat-related deaths and illnesses.
Outdoor Air Quality	Increasing temperatures and changing precipitation patterns	Worsened air quality (ozone, particulate matter, and higher pollen counts)	Premature death, acute and chronic cardiovascular and respiratory illnesses	Rising temperatures and wildfires and decreasing precipitation will lead to increases in ozone and particulate matter, elevating the risks of cardiovascular and respiratory illnesses and death.
Flooding	Rising sea level and more frequent or intense extreme precipitation, hurricanes, and storm surge events	Contaminated water, debris, and disruptions to essential infrastructure	Drowning, injuries, mental health consequences, gastrointestinal and other illness	Increased coastal and inland flooding exposes populations to a range of negative health impacts before, during, and after events.
Vector-Borne Infection (Lyme Disease)	Changes in temperature extremes and seasonal weather patterns	Earlier and geographically expanded tick activity	Lyme disease	Ticks will show earlier seasonal activity and a generally northward range expansion, increasing risk of human exposure to Lyme disease-causing bacteria.
Water-Related Infection (*Vibrio vulnificus*)	Rising sea surface temperature, changes in precipi-tation and runoff affecting coastal salinity	Recreational water or shellfish contaminated with *Vibrio vulnificus*	*Vibrio Vulnificus* induced diarrhea & intestinal illness, wound and blood-stream infections, death	Increases in water temperatures will alter timing and location of *Vibrio vulnificus* growth, increas-ing exposure and risk of water-borne illness.
Food-Related Infection (*Salmonella*)	Increases in temperature, humidity, and season length	Increased growth of pathogens, seasonal shifts in incidence of *Salmonella* exposure	*Salmonells* infection, gastrointestinal outbreaks	Rising temperatures increase *Salmonella* prevalence in food; longer seasons and warming winters increase risk of exposure and infection.
Mental Health and Well-Being	Climate change impacts, especially extreme weather	Level of exposure to traumatic events, like disasters	Distress, grief, behavioral health disorders, social impacts, resilience	Changes in exposure to climate- or weather-related disasters cause or exacerbate stress and mental health consequences, with greater risk for certain populations.

Fig. 7.1 The climate change impact on human health [153]

Accordingly, water bodies are contaminated, diseases are transmitted through food sources, air quality is degraded, which, consequently, bring cascading adverse effects upon human health and well-being. These problems are being exacerbated with rapid changes hence increasing exposure of the human for longer duration of time [143]. Therefore, new challenges are being faced in the area of human health [45, 100]. The climate and holistic health outcomes are shown in Fig. 7.2.

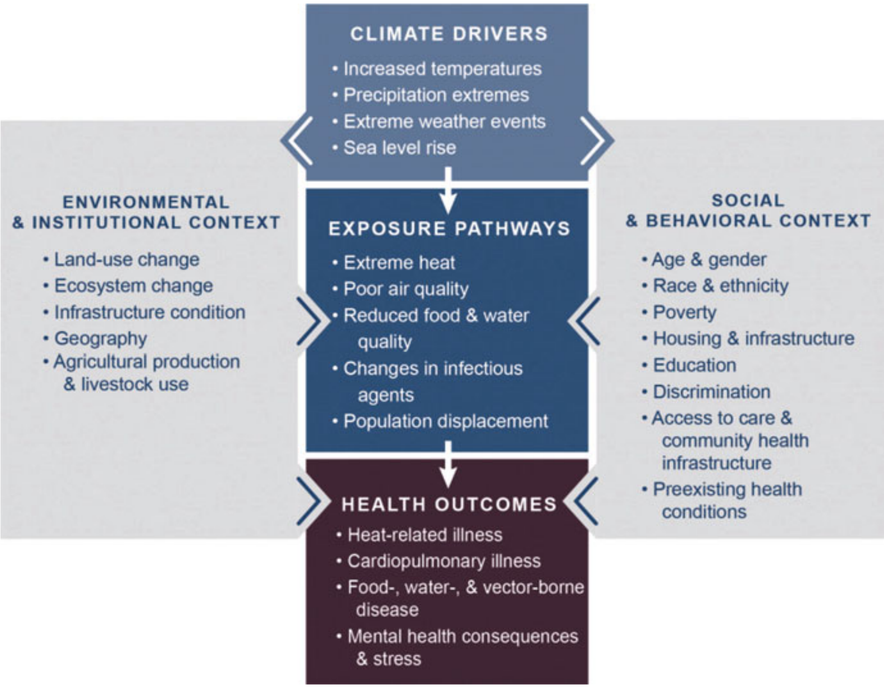

Fig. 7.2 The climate and holistic health outcome [153]

It is important to note that the magnitude of impact of climate on human health varies on spatial and temporal scale [72, 90, 119]. The children, elderly, poor, and sick are the ones most affected [10, 16, 79, 135, 140, 141]. The research has shown the high correlation between the mold and fungus related indoor air quality issues and the high and extreme temperatures, and heat waves and precipitation [48, 53, 64, 64, 75]. The moist indoor environment causes elevated prevalence of asthma and upper respiratory tract symptoms [2, 2, 39, 53, 70, 102, 128, 142, 148]. The extreme heat contributes to air pollution, and asthma, pediatric, deaths (e.g., hot cars), and increased frequency of emergency room (ER) visits, and hospitalization [7, 38, 91, 130, 159]. Similarly, the heavy precipitation also leads to severe flooding events, algal blooms, and waterborne diseases. The outdoor air quality is also affected by the wildfires which leads to respiratory issues because of smoke inhaling. The human health is also being impacted by the worsening air quality and pollution of the ozone [118]. The climate change has also led to expansion of scope of some disease vectors and other epidemiological factors, such as Ixodes ticks (Lyme disease vectors). The climate change also impacts the mental health and causes stress particularly after disasters and displacement. The summary of these climate change impacts is outlined below:

- The increased exposure to ozone [8, 15, 19, 50, 95, 125, 126, 151]
- Extreme weather events [1, 7, 52, 105, 116, 124]

- Rising allergens [108]
- Increase in frequency and intensity of wildfires [81]
- Thermal extremes [13]
- Growing harmful algal blooms (HAB) [9, 62, 114]
- Mental health stress [36, 57, 65, 66, 98, 106, 111, 145]
- Expansion of vector-borne infectious diseases [21, 83, 85, 93, 110, 117, 129, 136]
- More water- and food-borne diseases [32, 67, 88, 115]
- Food quality an security [56, 132]

7.2 Benefits of Sustainable Health IoT

The sustainable health IoT has tremendous potential to bring improvements in human health and well-being by enabling real-time sensing and monitoring of the climate induced impacts. These benefits are discussed below:

- Innovations in mobile health care
- Evolution of new sensing methods
- Novel communication techniques such as human body communications and molecular communications
- Remote diagnostic systems
- Human mobility models to predict diseases outbreak
- Support for remote telehealth and self-monitoring and tracking on diurnal basis
- Efficiency and improvements in health care settings
- Quick diagnosis of medical conditions
- Improvements in patient conditions management
- Development of novel treatment regimes

7.3 Sustainable Health IoT

The sustainable health IoT is characterized by its things which are the vital component of the paradigm for real-time sensing monitoring, medication compliance wireless communications, and imaging based decision support systems. In this section, the sustainable health IoT things are discussed.

- Patients, physician and health care providers
- Smart ingestible, implantable, and injectable medical devices
- Medicines, health, and wellness products
- Physiological, wearable, and molecular sensors
- Actuators, treatment, electronic health records
- Telehealth, precision medicine
- Insulin pumps, cochlear implants, and pacemakers
- Patient-generated and machine-generated healthcare data

7.4 Sustainable Health IoT Technology

In this section different technologies for sustainable health IoT are discussed.

7.4.1 Precision Medicine

The precision medicine is one of the emerging technologies in human healthcare [30, 96]. It deals with disease prevention and treatment approaches which are based on considering the human genetic, environmental, and other factors tailored to individual patients. The precision medicine practices are also called personalized medicine. The sustainable health IoT enables precision medicine by integrating DNA databases of clinical trials and application layer Health Level 7 (HL7) and other standards such as Fast Healthcare Interoperability Resource (FHIR) [120] to support treatments of different diseases.

7.4.2 Personalization of Diabetes Treatment

The sustainable health IoT also enables monitoring of the blood glucose levels in patients with diabetes [26]. By using sensing and wireless communications technologies, the advanced diabetes treatments can be utilized for extensive dissemination of blood sugar data to intelligent computing technologies and clinicians. There it can be evaluated for personalized treatment by generating prediction based cautions for insulin dosage and hypoglycemia updates.

7.4.3 Automated Nutrition Control

The sustainable health IoT enables automated nutrition control where based on daily calories needs, the customized food plan can be developed for patients by using the food ingredients. This enables suitable food choices based on the recommendations of the physicians. Accordingly, physicians can view the impact the food consumption on patient health for real-time decision making [61].

7.4.4 Mobile Healthcare Connectivity

The sustainable health IoT supports integration of wireless communications based interconnection of medical devices with the cloud for rapid on-line data management [144]. The Capsule Technologies Hub is a robust mobile gateway to

provide connectivity using many different wireless interfaces [35, 167]. The mobile healthcare connectivity in sustainable health IoT enables development of healthcare applications based on the wireless technologies that enables patient management and coordination and leads to higher efficiency and decreased cost of medical care.

7.4.5 Cancer Treatment

Cancer treatment approaches can greatly benefit from sustainable health IoT monitoring and communication technologies, where patients can transmit updates through symptom tracking applications to their physicians [127]. The physician's response is helpful to reduce the frequency of regular clinic visits. Moreover, the side effects of the medicines can be identified and addressed quickly. Early warning can be issued when the levels cross a threshold.

7.4.6 Glucose Monitoring

The sustainable health IoT facilitates continuous glucose monitoring (CGM) in diabetic patients. IoT enables devices can continuously monitor the blood glucose levels by providing regular readings for subsequent transmission to cloud using wireless communications and Internet with easy access through mobile devices by patients and physicians [51]. Accordingly, the automated delivery of insulin enables efficient management.

7.4.7 Smart Inhalers

The smart and connected inhalers (Bluetooth spirometer [168]) in sustainable health IoT enable asthma and other chronic obstructive pulmonary disease (COPD) [133], which includes emphysema and chronic bronchitis) patients to take control of their symptoms and treatments by using Bluetooth. These can also send reminders to patient about their medicine intake, hence, improving the disease management, attack avoidance, and symptoms reporting to physicians.

Other important applications include connected contact lenses to monitor variations in eye dimensions causing the glaucoma [6]; the coagulation testing for blood clot formations to avoid stroke, bleeding [165], assisted living [122]. Overall, the sustainable health IoT enables, through its sensing, communications, and monitoring technology, efficient health care, drug and chronic disease management, and reduction in emergency room wait times.

7.5 Sensing in Sustainable Health IoT

In this section, two types of health related sustainable health IoT sensing approaches are discussed: (1) the physiological sensing and (2) the environmental sensing for health [138].

7.5.1 *Physiological Sensing*

The physiological sensing is a vital monitoring approach in the sustainable health IoT to measure and analyze different physiological (biological) signals for medical and clinical healthcare applications [29, 164]. These data collected from these physiological sensor signals is discussed in the following:

- Heart rate (HR)
- Finger temperature (FT)
- Respiration rate (RR)
- Carbon dioxide (CO_2)
- Oxygen saturation (SpO2)
- Patient position sensor (Accelerometer)

The sensors to detect these physiological signals are given below [11]:

- Glucometer sensor
- Body temperature sensor
- Blood pressure sensor (sphygmomanometer)
- Pulse and oxygen in blood sensor (SPO2)
- Airflow sensor (breathing)
- Galvanic skin response sensor (GSR—sweating)
- Electrocardiogram sensor (ECG)
- Electromyography sensor (EMG)

A detailed review of these physiological sensors is given in [11].

7.5.2 *Ingestible Sensors*

These sensors are ingested in capsules or pills and have the capability to dissolve in stomach [84]. There, these are used to sense different physical parameters, which can be communicated to the external nodes through human body communications or by using wireless communications. The legal issues in ingestible sensors are discussed in [60].

7.5.3 Wearable Sensors

Wearable sensors are placed into wearable objects to sense different phenomena such as health conditions, environmental conditions, and physiological signals [11, 27, 54, 161, 166]. These can also be implanted in body from where they can communicate using human body or molecular communications. Some important use cases of the wearable sensors are listed below:

- Wearable devices for environmental monitoring [94] such as air quality [20, 22, 28, 42, 80, 99, 137, 157, 158]
- Wearable AI system to detect a conversation's tone [155]
- Wearable devices for physiological sensing [76]
- Wearable system to help visually impaired users navigate [156]
- Monitoring metabolic energy expenditure, health, and fitness with a breath analyzer [112]
- Wearable sensor for athletes detects potential head injuries, gathers data on hard hits [18]
- Wristbands that keep wearers thermally comfortable [112]
- Wearable tracks increased skin conductance that signals stress, helps identify dangerous seizures [104, 149]
- Wrist watch to monitor depression, and Parkinson's disease symptoms [113]

7.6 Environmental Sensing for Health and Wellness

In this section, the sensing of different environmental parameters and their impact on human health is discussed.

7.6.1 Sanitation, Waterborne Diseases, and Human Health

The viruses, bacteria, and protozoa are major cause of waterborne diseases also called water-related illnesses. The human-induced chemicals, toxins generated by cyanobacteria, and detrimental algae, are other sources of some of these diseases [23, 131]. The patients are also exposed to these diseases when the contaminated water is inhaled or ingested. Other recreational activities in contaminated water and eating contaminated seafood are also a cause of waterborne diseases. The water-related illness grows, spreads, and becomes viral and toxic based on different climate related factors such as hurricanes, precipitation, runoff, and storm surges [32, 88]. Moreover, the exposure to these diseases also depends on individual's capacity of adaptiveness and sensitiveness.

Fig. 7.3 Water related health issues [153]

The waterborne diseases are also major challenge in urban areas where the 6–40% of gastrointestinal illness are caused by extensive contamination of wells and surface water by various pathogens. The access to safe drinking water is also a major global issue with one billion population lacking access to safe potable water. Moreover, the increasing global temperatures are fostering production of toxic algal blooms. These organisms are serious risk to human health (see Fig. 7.3) [153].

The sustainable health IoT through its sensing of water quality, real-time monitoring and warning systems, and other treatment technologies enables effective prevention and mitigation of diseases caused by water contamination. It enables water flow and quality monitoring. The water quality sensing also informs the selection of proper disinfection technique based on pathogen sensing and molecular sensing methods for specific pathogens and their ability to cause infection.

The sustainable health IoT holds great promise in water quality improvements and sanitation in less developed and advanced countries. Some examples are presented in the following:

- The smart meters and reverse osmosis (RO) technology in IoT systems and sensor networks is being used in India for provision of clean water and for water treatment to rural areas [134].

- The IoT technology is being used in China to monitor the water flow and usage by using sensors installed at different points in the water supply system [147].
- A biosensor network is utilized in Bangladesh for water quality monitoring using arsenic sensor [41].
- In Kenya, a smart connected water hand pump is being used to address the issues related to the non-functional water pumps for timely maintenance [92]. Special accelerometer based devices were designed and installed with built-in 3G radios for water hand pump monitoring. With battery life of up to 18 months, this IoT system has reduced downtime while ensuring consistent water supply service delivery.
- For sanitation and hygiene, the water flow and motion sensors are being used in Indonesia to identify human behavior (e.g., hand washing after toilet use) and to design enhanced hygiene training [152].

7.6.2 Ultraviolet Radiation and Human Health

The exposure to ultraviolet radiation (UV) can have multiple impacts such as corneal damage, skin cancer, sunburn, immune suppression, and cataracts [12]. The detrimental effects of ultraviolet radiation include damage to plastic, wood, and other infrastructure. Overall, UV radiation presents many challenges to health and environment.

The sustainable health IoT has the potential for robust monitoring of ozone and UV radiation levels at a large scale, which can be integrated to the cloud for new insights. Accordingly, models can be developed for informed decision making. A sensor called dosimeter determines the UV exposure by measuring absorbed amount of ionizing radiation. The ionizing radiation at its peak is capable of removing an electron from an item. A urocanic acid photoreceptor is used for the induction of UV immune suppression. The UV-induced (UVB induced) immune suppression is variation in cell immunity which produces suppressor cells. Various types of ultraviolet radiations and related concepts are discussed below [71]:

- UVA. The UVA has the longest wavelengths 0.31 micrometer to 0.4 micrometer and impacts skin aging. The ability of atmospheric gases to absorb UVA radiation is low. Therefore, UAV are able to reach surface of the Earth.
- UVB. It causes skin burning and suppression of immune system with its shorter wavelength of 0.28 micrometer to 0.31 micrometer. However, most of it is absorbed by stratospheric ozone.
- UVC. The UVC is mostly absorbed by the ozone and oxygen present in the atmosphere. It has shorter wavelength of 0.1 micrometer to 0.2 micrometer. UV-C radiation is almost entirely absorbed by atmospheric oxygen and ozone.

7.6.3 Extreme Weather and Human Health

The thunderstorms associated increased humidity levels are known to cause cardiovascular and respiratory diseases [44]. The natural disasters also contribute to the mental health issues (e.g., post-traumatic tension disorders). Moreover, the prolonged duration of the hurricanes, tropical storms, and extreme weather events also causes short-term stress related issues with its disruptions to subsistence activities and to different modes of transportation, affecting overall health and well-being.

7.7 Wireless, Human Body, and Molecular Communications in Sustainable Health IoT

The applications of wireless communication technologies to human health are being used for sensing, data collection, modeling, and analysis of health information of patients using Internet and various computing technologies [55, 59, 121, 162, 163]. Wireless communications play an important role to provide connectivity to sensors and system in sustainable health IoT in different topologies and configurations. The Bluetooth (IEEE 802.15.1) and Bluetooth Low Energy (BLE) are commonly used for this purpose due to its low cost and energy requirements along with other standards such 4G, WLAN, LTE, UMTS, Wi-Fi, and WiMAX. A list of different wireless technologies for sustainable health IoT applications is given below:

- IEEE 802.11x (Wi-Fi) is the widely used wireless local area network protocol for health applications. It operates in 2.4 GHz or 5 GHz frequency bands. The latest versions of the Wi-Fi can support data rates from 54 Mb/s to 0.5 Gb/s with communication range of more than 100 m [74].
- IEEE 802.15.1 (Bluetooth) operates in 2.4 GHz frequency band with communication range of up to 10 m. and supports data rates of 722 Kb/s for the classic version (BC) and 3 Mb/s for Bluetooth Enhanced Data Rate (EDR) [17].
- Bluetooth Low Energy (BLE) is a low power variant of Bluetooth. It can cover communication distances of up to 68m with maximum data rates of 1 Mb/s. It uses physical and data access layer of Wi-Fi.
- ZigBee (IEEE 802.15.4) is a less complex, low cost and data rate, wireless personal area network (WPAN) standard for prolonged operation of devices and equipment. It supports 868 MHz frequency, 915 MHz spectrum band, and 2.4 GHz radio wireless channel with maximum data rates of more 250 kb/s, respectively, for communication range of up to 75 m [169].
- Long range wide area network (LoRaWAN) has the potential for long range communications in sustainable health IoT applications (e.g., the LoRa) It also supports 868 MHz frequency and 915 MHz spectrum operation with data rates of more than 50 kb/s [37].

- Chirp spread spectrum (CSS) based nanoLOC operates in 2.4 GHz frequency band. It covers communication distances of up to 570m depending on the environment with data rates of up 2 Mb/s [139].

  More details about wireless body area network can be found in [68].

7.7.1 Human Body Communications

The human body communications (HBC) is another important connectivity mechanism in the sustainable health IoT. Body is a highly conducting material (body tissues are lossy dielectric) because of the presence of the water and blood. Human body communications also are very energy efficient and require very low power for operation for implanted medical devices with long battery life, hence reducing the inter-surgery time significantly. Moreover, the human body communications are very secure and present resistance by preventing physical access of devices by hackers. These can be utilized to form the inter-body and body-to-body communication networks wearable sensors and devices, implanted medical devices, in-body authentication instruments in the sustainable health IoT [55, 58, 78, 107, 164].

The wearable sensors can establish connection using HBC for critical data communications to external devices. The body area network (BAN) in the IEEE 802.15 working group has developed a physical layer (PHY) for human body communications. In HBC, there are three main components: (1) the human body channel, (2) radio system, and (3) modulation and transmission schemes.

Another alternative to wireless body area network (WBAN) is electro-quasistatic human body communication (EQS-HBC) [34], which operates by broadband low frequency human body communications to achieve secure data transmission. A comparison of WBAN and electro-quasistatic is presented in Fig. 7.4.

7.7.2 Molecular Communications in Sustainable Health IoT

The molecular communications (MC) form the basis of the information transmission within basic unit of human life such as biological cells and complex organisms [4, 97]. In molecular paradigm, the data bits are modulated on molecules and communication propagation happens through the transport of these molecule and chemical reactions. The fundamental building blocks of the molecular communications are shown in Fig. 7.5 and are discussed below [4]:

- Molecules are the smallest distinguishable unit of a chemical compound and represent atoms bind together in the chemical composition of a particular substance [3].
- The chemical reactions are the manipulations and transformations resulting from the detachment and formation of molecules.

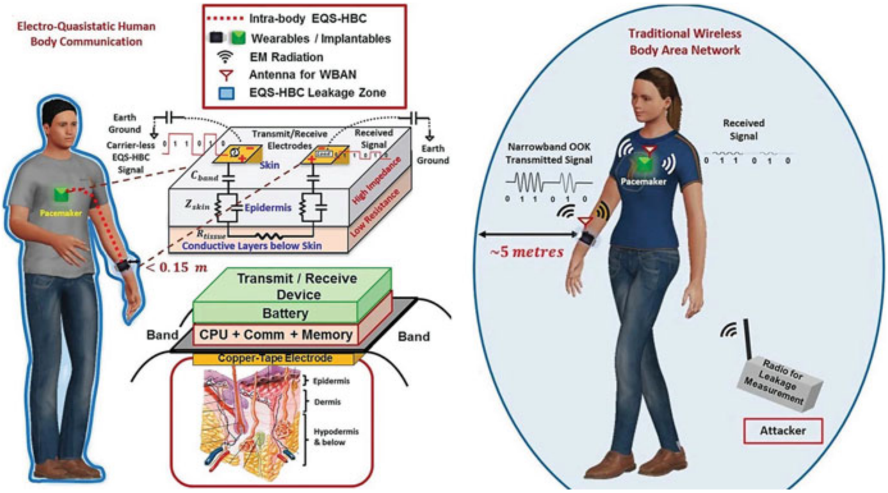

Fig. 7.4 A comparison of WBAN and electro-quasistatic human body communications [34]. EQS-HBC vs. WBAN: An Overview of the Data Privacy Space, (**a**) Persons wearing transmitter device (pacemaker) and an on-body hub communicating using EQS-HBC and (**b**) WBAN

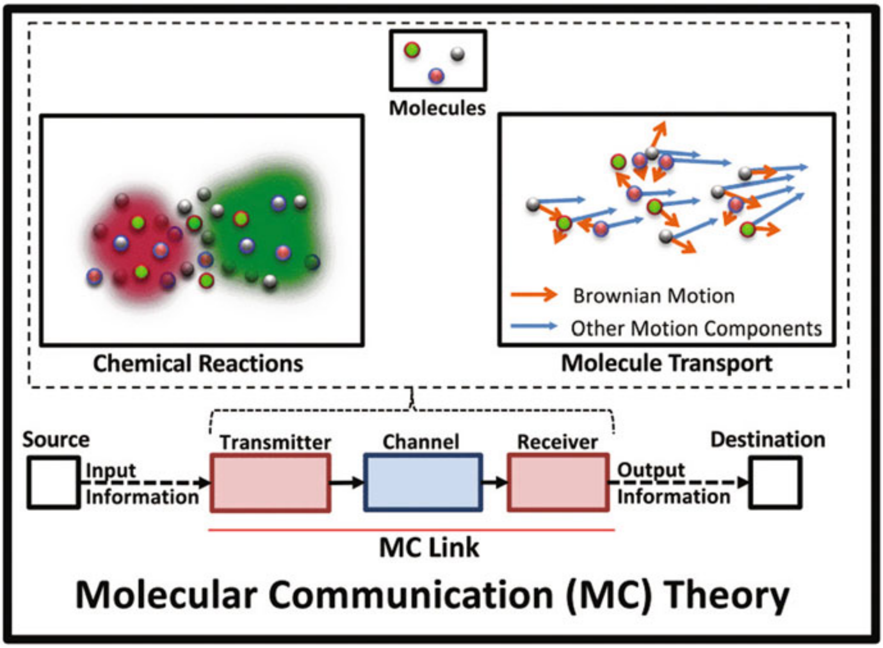

Fig. 7.5 The fundamental building blocks of molecular communications [4]. From moving forward with molecular communication: from theory to human health applications

- The molecule transport is the process of their propagation in space and happens through flow, transport, Brownian forces such as movement in the blood runnel or intra-cells motion [3].

The components of MC system include a transmitter, molecular channel, and a receiver. The communication channels propagation depends upon various molecular transport models such as chemotaxis, gap junction, diffusion, and molecular motor. The current research focus in MC is to maximize data communication rates, and development of coding and information modulation approaches, and the design of suitable modulation and coding techniques, and novel networking topologies for optimization of molecular data communication by molecules using multiple segments simultaneously [103].

The MC enables the sensing and monitoring applications through its propagation living organisms and the biochemistry underscoring the human body and cells (e.g., the cancers caused by the malformations polarity, and growth of molecules). The MC systems are envisioned to advance human health informatics and enhanced medicine with applications in natural and synthetic systems.

The monocular communications information flow theory in natural systems can model:

- At body scale, where a system is considered as an interconnection of tissues and organs.
- The cell coordination at cellular scale.
- The information modulation into compounds for subsequent propagation through chemical reactions and molecular transport.

For synthetic applications, the MC applications for system engineering purpose are:

- At interface level: Use of synthetic biology tools to develop genetic programs
- At device level: Development of bioengineering systems, programmed to perform specific actions.
- At network level: An interconnection of bio-engineering systems human health monitoring and connectivity to cloud

These applications of natural and synthetic systems of molecular communications in sustainable health IoT are shown in Fig. 7.6.

7.8 Sustainable Health IoT Systems

In this section, various systems, tools, databases, and indices to achieve sustainability using Internet of Things.

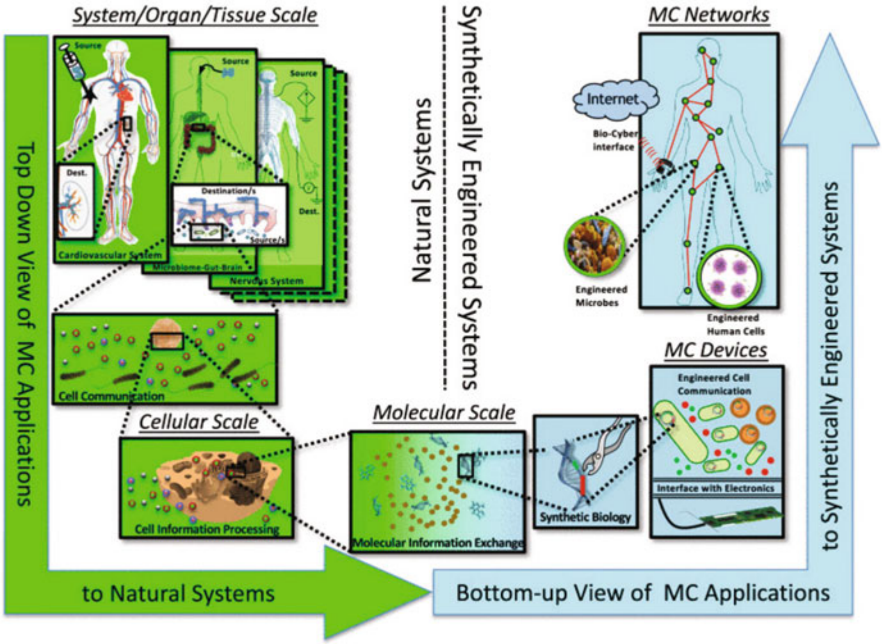

Fig. 7.6 Applications of natural and synthetic systems of molecular communications in sustainable health IoT [4]. From moving forward with molecular communication: from theory to human health applications

7.8.1 Health Indices

The vital health indices related to the environment are discussed:

- UV Index. This index is used to predict the solar UV radiation. The UV index is a number, measured on a scale of 0 to 11, that reflects the diurnal threat of sunburn (over-exposure to sunlight). The value of 0 represents the minimal exposure and an index value higher than 10 indicates extreme risk to human health [154].
- Environmental Health Hazard Index. The US environmental health hazard exposure index provides information about harmful toxins exposure neighborhood levels [49]. These health hazards exposures are determined using linear combinations of estimates of air quality respiratory, carcinogenic, and neurological hazard with indexing census tracts.
- AirNow: The air quality index (AQI) is an index to monitor the air quality and pollution. Accordingly, it informs about the related impact concerning human health [5]. It is ascertained by considering four air pollutants: particle pollution, carbon monoxide, surface ozone level, and sulfur dioxide gas.

7.8.2 Environmental Public Health Tracking Network

This US tracking network contains data and information on health effects, environmental hazards and substances, and human health [24]. This is an important data source for measuring hazardous substances in environment. The main features of the environmental public health tracking network are outlined in the following:

- It provide insights about spread of these substances over spatial and temporal scale and their impact on human tissues (e.g., carbon monoxide and air pollution in the environment).
- It also hosts data about health conditions and diseases, such as asthma and birth defects.
- It also contains exposure data. It contains vital information about the exposures relationship with the health effects, which relates specific health problems to age, race, sex, and behavior and lifestyle choices.

7.8.3 Mobile Health-Care Innovations

The mobile technology is an emerging innovation in healthcare solutions. Mobile applications are being developed to address mental health, cancer, active sports therapy, and rehabilitation with capability to support large-format displays, Bluetooth pen, AI, and cameras. These mobile technology when integrated with sustainable health IoT holds massive potential to make a profound impact by providing valuable healthcare services, such as telehealth [77], virtual care, and remote patient monitoring.

7.8.4 Mobility Models and Health

The human mobility models are used to analyze the population movement which can be used to mitigate disease outbreaks (e.g., development of malaria eradication strategies) [43]. During the 2014 Ebola outbreak in Sierra Leone, Guinea, Nigeria, Liberia, and Senegal, the call detail records (CDRs) from mobile cellular wireless network were used to monitor population movements through development of epidemiological models. These mobility models were used to forecast the spread of Ebola and potential outbreak of disease through analysis of movement paths of the affected population. The privacy concerns and security related issues are some of the major challenges in implementation of this approach in sustainable health IoT [82].

7.8.5 Virtual Beach

This virtual beach is a decision support system to predict disease-causing pathogens at beached. The policy makers can utilize the statistical model for health related beach decisions. It is also to issue alerts about the concentrations of fecal indicator bacteria (FIB) concentrations observed at beaches [33].

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Chapter 8
Internet of Things for Sustainable Mining

Abstract The sustainable mining Internet of Things deals with the applications of IoT technology to the coupled needs of sustainable recovery of metals and a healthy environment for a thriving planet. In this chapter, the IoT architecture and technology is presented to support development of a digital mining platform emphasizing the exploration of rock–fluid–environment interactions to develop extraction methods with maximum economic benefit, while maintaining and preserving both water quantity and quality, soil, and, ultimately, human health. New perspectives are provided for IoT applications in developing new mineral resources, improved management of tailings, monitoring and mitigating contamination from mining. Moreover, tools to assess the environmental and social impacts of mining including the demands on dwindling freshwater resources. The cutting-edge technologies that could be leveraged to develop the state-of-the-art sustainable mining IoT paradigm are also discussed.

8.1 Introduction

The mining is the process of acquiring minerals from mines. In addition to the resource development, it has many economic, social, and environmental aspects. Recently, considerable progress has been made towards attaining sustainable mining practices and improving environmental quality [10, 13, 39, 41, 48]. Moreover, significant technical developments have also improved the mining practices. However, there are substantial efforts required to make mining sustainable [2, 32, 60].

8.1.1 Sustainable Mining

Apparently, it seems that there is no compatibility between the mining operations and sustainability and both seems contradictory due to the limited nature of mining resources. Since the sustainability is related to capability of maintaining a certain level of resources for current and future needs, the sustainable development in

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mining is difficult to achieve if the rate of the minerals extrication process continues to increase the replenishment rate of the geological processes [59]. The advances in mining practices (e.g., sensing, monitoring, and communications technology development) are needed in the areas of explorations, mining, and metal processing to improve productivity, safety, and health [29]. In 2002, the International Council on Mining and Metals (ICMM) Council espoused the Toronto Declaration for the Global Sustainable Development Initiative (MMSD) that underscores the value of technology tools and systems for the sustainable development (SD) initiative [51]. It also highlighted the importance of the best-practices and verification protocols, best-practice protocols, and reporting for SD. The importance of the integrated mines and material management throughout the minerals value chain was also emphasized.

The mining practices conducted keeping in view the environmental and socio-economic factors and the sustainable development goals (SGDs) are considered sustainable [10]. The exploration and development of novel technologies also makes mining sustainable. The three vital factors of the sustainable mining are:

- Analysis of current and future demands in mining
- Development of integrated approaches for decision making and adoption of practices based on SGDs and community involvement
- Advancements in metal recycling and reclamation methods

8.1.2 IoT for Sustainable Mining

Mine monitoring techniques seek to establish a proper environment to avoid accidents, destruction of equipment, loss of ore reserves, and closure of the mine with greatest effectiveness. Accidents happen because of roof fall and side fall that often take toll of human lives [56]. Proper mine monitoring minimizes these loses, maximizes response to other management practices, and optimizes mining. Mining management without real-time monitoring can also significantly reduce the potential for profitability. Proper mine monitoring using IoT will help to reduce the potential for runoff, run-on, deep percolation, nitrogen and other chemical leaching to the ground and surface water resources, and reduce soil erosion and mine contaminant movement into surface and groundwater [14].

Among existing techniques, Internet of Things in Mine Monitoring (IMM) is a growing technology in mining operations [9, 11, 19, 20, 53, 57, 62]. However, there is a significant lack of data and procedure development in terms of fundamental understanding and quantification of mine minerals. Current mine sensing technologies are not best suited to provide IMM systems with almost real-time minerals data to facilitate fast decision making. Thus, accurate monitoring cannot be applied at the right place of a mine at the right time. Failure to consider the monitoring in active working face, goaf, and sealed off areas in mining decisions results in mining accidents. Accordingly, human lives are wasted and the potential for chemical leaching from the mine is increased.

Timely information of temporal and spatial mining patterns can significantly aid mining producers in better managing their mine operations to achieve higher production efficiency. Real-time knowledge of spatial contaminant distribution can also further advance our understanding of variable soil water and minerals distribution as well as mine dynamics. Accordingly, more effective IMM strategies can be developed to enhance productivity and reduce leaching. This improvement, conservatively, can result in significant dollar savings. Challenges in communication between within-field sensors and decision making systems, however, prohibit these research results to be successfully transformed into wide-spread mining practices. In general, sensors can be buried at different depths and wired to a data logger above the surface, which can be used for manual data collection or wireless data transfer. Manual data collection is labor-intensive and requires significant amount of travel time. More importantly, by the time when the data are incorporated into decision making, it is late to achieve proper mining actions. Thus, mining companies, especially those with large-scale mining operations, are looking for more effective, within-field, faster, and more robust data harvesting technologies.

On the other hand, existing wireless communication solutions are disruptive to mine operations. A tower and temporarily installed sensors need to be deployed before exploration and must be retrieved during constructions due to the interference of the sensors and towers with the mine operations, adding to the maintenance, labor, and time costs. Moreover, high costs prohibit sensors to be deployed in multiple locations in a mine. Accordingly, mine variability cannot be captured by existing techniques. As a result, the spatial and temporal variability of the field and mine conditions cannot be accounted for within mine monitoring decisions. This project will address real-time and variable information acquisition challenges to enable autonomous mine monitoring solutions guided by in situ sensor information. It enables autonomous decision making for mining operation, minimize or eliminate the human error associated such decisions, and enhance operation efficiency. The sustainable mining IoT is envisaged as to provide key infrastructure and technology advancements for the next-generation integrated mine monitoring (IMM) practices, in which mining systems are tightly coupled with proper underground mine minerals monitoring. These systems have the potential to provide significant advancements for mine monitoring in unmanaged or poorly managed systems, where mining decisions are not based on quantitative sensor indicators. To this end, novel wireless underground communication techniques in IoT can be employed.

- Real-time Mining Sensory Data: Communication challenges prohibit real-time information gathering from highly variable mines (both spatial and temporal variability) with multiple sensors. The recent wireless underground communication techniques provide tools to gather real-time mineral information. However, real-time information has not yet been collected from practical mine fields. The sustainable mining IoT can be utilized for real-time data collection.
- Autonomous Mine Monitoring: The theoretical/scientific understanding of real-time and/or autonomous mine monitoring has not been well established for mining efficiency improvement. This is partly due to lack of technological

advances that enable such data collection and autonomy on a mine scale. Even when the data collection from the mines that have spatial and temporal variability is accomplished, a scientifically- and research-based practical tool for integration of all these data and information into central location for decision making for IMM does not exist. There is need to develop such a tool to integrate real-time mine disaster monitoring and early warning system coupled with environment data to allow effective and fast decisions for proper IMM practices.

- Field-based Mining Prescription: Mine monitoring practices heavily rely on the field properties, mineral type, mine type, climate, and more importantly, their interactions. Consequently, it is not possible to develop one-size-fits-all solutions. Instead, deep understanding of advanced mine monitoring tools for different fields is required so that mine monitoring prescriptions tailored to these properties can be developed and applied in various field conditions. These insights necessitate the development of a proof-of-concept sustainable mining IoT architecture for autonomous mine monitoring that enables extensive experimentation of next-generation mine monitoring practices in different types of fields.
- Sustainable Mine System Operation: The real-time mine disaster monitoring and early warning systems have the potential to transform mining practices to help realize more efficient and sustainable mining solutions. Within this broader context, it is also important to devise sustainable system solutions for underground sensing systems. To this end, it is desirable to improve system efficiency in terms of communication reliability and energy consumption. With the long-term vision towards developing fully automated mine monitoring solutions, the mining IoT paradigm supports development of autonomous system that enables autonomy in mine monitoring with a capability to evaluate technology in practical conditions to devise autonomous mine monitoring solutions that advance mining practices. The sustainable mining IoT can be realized through advanced sensing, communication solutions, and information systems. An overview of sustainability mining IoT components is presented in Fig. 8.1.

8.2 Sustainable Mining Things

The mining methods are classified into four types depending on the type of the ore deposits(depth and inclination), depth, strength, and thickness of the rocks, roof/floor type. These are shown below:

- Surface mining for shallow deposits
- Underground mining to access deeper deposits
- In situ mining and augering to dissolve minerals in place
- Placer mining for shifting and placement of mineral

Fig. 8.1 Overview of sustainability mining IoT

The sustainable mining IoT things are presented in the following:

- Metals, mineral deposits, ores, rocks
- Mining-influenced groundwater and surface water
- Mineland, subsidence, land use, and reclamation
- Tailings, acid rock drainage
- Solid wastes, effluents, waste rock, and soil
- Hazardous materials

8.3 Research Challenges in Sustainable Mining IoT

In this section, various research challenges to enable technological drivers in sustainable mining IoT are discussed.

The development of novel sensors and sensing techniques is vital for sustainable mining IoT [24]. This includes analytical sensors to detect chemical and mineralogical properties of ores and rocks with portable, mobile, fixed static settings [8, 21, 23]. For geophysical sensing, the aircraft and drones technology holds promise for seismic sensing [52] of surface features at shallow depths and hyperspectral sensing for detailed 3D analysis and to produce the geo-hydrological, chemical, and environmental models needed for ore deposits [18, 34]. The alternatives to seismic sensing are electromagnetic (EM) sensing and ground penetrating radar (GPR) [1, 12, 16, 58]. The ore-grade analyzing systems can be utilized for mineral quality and quantity assessment in both surface and down-hole configurations [49]. The sustainable mining IoT has the potential to integrate different type of sensors such as location sensors, gas, obstacle-detection, and water quality sensors. Models and simulations are also needed for to get better insights into mineralogy, geological and hydrological processes in mines, and rock and soil properties [26, 31]. Moreover, the sensing data integrated would be beneficial for sustainable mining IoT decision support systems. These innovations in sustainable mining IoT will lead to reduction in lead times and improve the efficiency of recovery process.

The availability of variety of sensing and detection method is useful to get better perspective and resolution in different applications of sustainable mining IoT [24]. Real-time data processing and visualization techniques can be used to display the mine data for different type of mining applications. Moreover, channel models are needed for the mine based communications channels for in-mine and mine to surface communications [38, 45]. Robotics can be utilized to automate mining operations such as nonexplosive rock fragmentation, drilling, transport, and mapping. The need of the total resource recover in mines without impacting the environment cannot be overemphasized [43, 46, 65]. The advancements are needed in fine and ultra-fine minerals and particles recovery such as techniques to separates solids and liquids [54]. In this regard, developments of novel in situ methods to access deposits where ore permeability is low including casing, fracturing, rubblization techniques for in situ leaching and boreholes mining, and drilling [27]. The reduced cost of biomining approach where bio-agents are used to extract mineral will reduce waste and environmental impacts. In this regard, integration of innovations in biomedical, chemical, and physical sciences integration with mining practices will aid to attain sustainable development goals. The fracture process in mining consists of blasting, rock fracturing, drilling, excavation, comminution. Currently, hydraulic fracture process is applied to petroleum and geothermal mining. It has many negative effects on air and water pollution. It has higher probability of oil spills with harmful impact on vegetation and soil. The sustainable mining IoT is envisioned to bring technology in cutting and fragmentation, where computer-aided cutting and blasting can inform the optimal fragment size with accurate procession. It can also

reduce the dust by reducing the processing time and thrust and improved timing and tailoring of explosives. Moreover, for sustainable mining, the development of efficient water treatment is necessary for mining-influenced water (MIW) [50]. The mining process will benefit from developments in dewatering [33], dissolution of minerals [40], flotation [64], grinding and classification and other developments in chemical reagents [47], electrochemistry [61], thermodynamic and kinetic data [28], and microbiological agents [55].

The proper monitoring of mining pollutants is important to ensure that nearby water bodies are not impacted from it [63]. For environmental monitoring applications, sondes are used to sense conductivity, TDS, pH, salinity, and other parameters [3]. The development of strata control procedures is important for effective slope monitoring where excavation and rock properties (rock mass and intactness) is observed for stability and safety [22]. The improvements in technology for difficult-to-mine deposits (e.g., thin coal seams) in longwall and continuous coal mining approaches are needed [15]. The existing directional drilling technology of petroleum and geothermal drilling can be applied. Moreover, in geochemical and geophysical exploration systems, there is need for portable and down-hole analytical equipment to characterize cross bore hole and to get improved insights into soil particles mobility. Use of drones in aerial geophysics will improve shallow seismic methods and better representation of hyperspectral data [35, 42].

For mining operations, the industry can benefit from research in advanced imaging methods with capability to propagate through surface vegetation and cover. The increased resolution and coverage is needed for magnetic, radiometric, gravitational, and spectral methods. For mineral processing, potential research avenues are to make advances in flotation systems, blasting alongside crushing, finding alternatives to electromechanical energy and phosphogypsum production, and modeling, and autonomous control. Similarly, innovations in hydro-metallurgical and bio-technological techniques will advance metal extraction.

8.4 Sustainable Mining IoT Technologies and Monitoring Systems

The exploration (mineral identification), drilling, comminution (breaking to separate ore and waste), resource gathering, production, processing (crushing and grinding), closure, and land reclamation are important steps in the life cycle of the mine [17, 25, 36]. Therefore, the development of new technologies in these areas to reduce the environmental impact and waste will be beneficial for sustainable development. Due to hazardous and complicated conditions of mines, continuous monitoring of mines and early warning systems is vital to ensure safety, to avoid health-related issues in miners. These disastrous events in mines include fire, explosion, water surge, and roof fall [4]. An architecture of sustainable mining IoT is shown in Fig. 8.2.

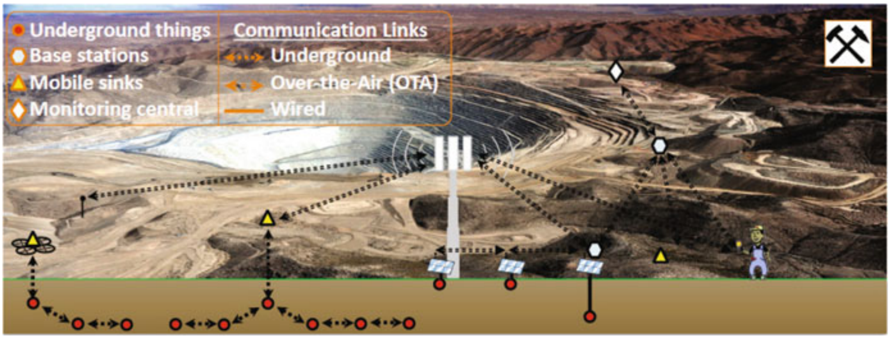

Fig. 8.2 The architecture of sustainable mining IoT

The sustainable mining IoT technologies and monitoring system collect data using different types of sensors and transmit this information to the database and cloud by using wireless communications. In this section, the technologies and monitoring systems for sustainable mining IoT are discussed.

8.4.1 Mine Monitoring for Health and Safety

The sustainable mining IoT is useful to monitor the safety conditions in mines, where technology is used to detect obstacles and obstructions to avoid hazards such as fall, berm, and equipment. The robust and reliable technology can also be used to assess health conditions in mining atmosphere to sense and identify the miners mix-mode exposure to the oxidation, dust, diesels, and cutting pollutants. By using wireless communications, this information is then used for real-time alert system. Moreover, the lack of proper mine ventilation is another important health concern in mines. The presence of sufficient amount of oxygen is necessary to support breathing. Sustainability IoT based mine ventilation systems are used to monitor air quality, cooling and control the air movement through direction and blocking.

8.4.2 Environmental Monitoring

The environmental monitoring in sustainable mining IoT is vital to protect the environment. For acid rock drainage, the acid-generating materials are identified to lessen and remove accumulation in pit floors and walls and to prevent encapsulation of wastes and passivation. Accordingly, the acidic wastewater and pit water can be treated by removal of metals and nitrate and novel techniques of dewatering and

consolidating slimes can be developed. Through sensing and improved predictive modeling the cyanide can be destroyed in situ. The new technology is needed to aid evapotranspiration, impede infiltration, and fine particle emission.

8.4.3 Earth Crust Monitoring

The integrated mine monitoring system can be used to monitor the Earth's crust, where different type of subsurface sensors are used detect seismic activity and other underground conditions. The ground motion, displacement, and other disturbances can also be measured. The seismometers and vibration sensors are examples of some of the sensors used in earth crust monitoring. Because of the mining stress and deformations, the equilibrium of mine strata is disturbed. It depends on the mining technique used, rock mass and other proprieties, and depth of the strata. Accordingly, it results in falling rocks in mines. Therefore, the sustainable mining IoT can be used to ass stains, load, stress, and deformation by using extensometers, electromagnetic and mechanical methods including linear variable differential transformer (LVDT), strain sensors, micro-electro-mechanical systems (MEMS), resistance sensors, stress sensors, and vibration sensors.

In the opencast mining, a large amount of overburden is removed. With continuous accumulation of waste, the dump level can increase and becomes susceptible to failure. Similarly, in open-pit mines, the sheer slants can fail and cause damage to mine equipment and machinery. Therefore, a slant strength monitoring system in sustainable IoT can be used to monitor the firmness of the dam and sheer slants using geo-sensors which can monitor different parameters (e.g., roof load and convergence, pillar pressure and seismic activity resulting from blasting and fracturing).

8.4.4 Transportation Management

The sustainable monitoring system can be used to monitor the different aspects of the transportation in the mining such as mineral measurements and vehicle loading, route management, and illegal vehicle activity to detect unauthorized access. This information can be viewed in real-time using wireless communications. The examples of sensors used in these systems are inductive loop, IR, and ultrasonic sensors, and acoustic arrays.

Moreover, mining machinery is often used under high load conditions. The machinery monitoring in mines is done using the sensors installed on the machinery for the purpose of health, load, location, and fuel assessment. The sustainable mining IoT enables prediction and early warnings of machinery faults using sensors

such as thermocouples, accelerometers, acoustic sensors, and tachometers The sustainable mining IoT has the great potential to benefit in real-time decision making, production management, and projections on resources. Through this paradigm the mining machinery (e.g., dumpers and shovels) can be minimized which leads to profit maximization.

8.4.5 Gas Detection

The gas emissions in mines are caused by either burning or from the crust of the earth due to seismic event, displacement, and rock fracturing. Miners come into contact with these various types of inflammable and toxic gases in mines such as nitrogen, carbon monoxide, sulfur dioxide, methane, carbon dioxide, and hydrogen sulfide. The sustainable IoT gas monitoring systems are used to mitigate and monitor gases using different types of sensors and chromatograph. Accordingly, real-time warning and alarm systems are developed. To monitor methane, the catalytic ball sensors are used to accurately sense different levels of methane. However, the different factors such as exposure to high concentration of gases, silicones, and hydrogen sulfide negatively affects the performance of the sensor. The local methane detector (LMD) works operates by using IR sensing. Accordingly, improved techniques for collection of methane drainage and dilution.

A summary of site monitoring and characterization techniques for gas is given below:

- Biosensors
- Colorimetric test kits
- Detector tubes
- Fiber optic chemical sensors (FOCS)
- Fourier Transform Infrared Spectroscopy (FTIR)
- Gas Chromatography (GC)
- Gas Chromatography/Mass Spectrometry (GC/MS)
- Graphite Furnace Atomic Absorption Spectrometry (GFAA)
- Gross counters
- Immunoassay test kits. Three categories of field analytical methods use biological systems to measure target analytes: Immunoassays, immunosensors, and enzyme-based assays that do not require the binding of an antibody to a target analyte as antigen
- Inductively Coupled Plasma Spectrophotometry (ICP)
- Liquid Chromatography (LC)
- Membrane Interface Probes
- Mercury vapor analyzers
- Surface Acoustic Wave Sensors (SAWS)

8.4.6 Goaf Fill Monitoring

The goaf is cave formed due to mineral extraction in the underground mines such as in coal and classified into working (active) and sealed (closed). The subsidence is caused by the goaf formations. Therefore, the stowing is used to pack the different material (soil, sand, and rocks) in order to fill goaf. The monitoring of the strata in goaf is important to assess the stability and strength of the structure and to reduce subsidence. The gas accumulation in goaf carries the risk of explosion. Therefore, goafs are also monitored using gas sensors.

8.4.7 Mine Fire Monitoring

One major concern in mines is fire hazard. The mine fire causality is attributed to friction, explosions, and combustion. The coal mines are more prone to mine fires as compared to the mineral mines because of being innate oxidized. In coal mines, fire proliferation process is very rapid. Therefore, accurate and robust fire warning systems are needed. The sustainability mining IoT enables fire detection, control and warning systems through sensing of temperature, and gas. The IR sensors are used for the purpose of temperature at various locations in the mines. The ratios of concentration of oxygen and carbon monoxide at various places in mine needs continuous sensing. Accordingly, alarm is generated based on the threshold values. The 3D temperature maps are also helpful in mine monitoring.

8.4.8 Conveyor Belt Monitoring

A conveyor belt is used in many mines for long haul mineral and coal transport. The conveyor belt monitoring includes broken ball and idle bearings, broken cage, and failure detection on the belt. A fiber optic cable alongside the belt which detects these failures by using pulse transmission and Rayleigh back-scatter. Accordingly, the sustainable mining IoT enables smart conveyor belt control, sensing, and communications systems.

8.4.9 Water Monitoring

The groundwater is significantly impacted by the mining activities. The groundwater incursions happens because of the cracks and geological faults in structures and high water pressure and the temperature. The water properties monitoring is important due to many factors to prevent the water related hazards and to prevent deterioration

of water quality. The groundwater has high resistivity (reciprocal of conductivity). Hence, resistivity based geophysical sensing methods are employed to water sensing in sustainable mining IoT.

8.4.10 Miners Tracking

By using miner tracking, the fall hazards can be detected and trapped miners can also be located in case of accidents. The localization methods are used to locate miners in mines. The wireless and wires localization approaches are utilized by using general communication equipment such as routers. Accordingly, the 3D maps can be produced showing mine workers location.

8.5 Paradigm-Shift Technologies for Sustainable Mining IoT

Many novel paradigm-shift technologies are emerging in mining.

- Autonomous mining. In this fully robotic based mining process, the robotics systems are used for underground mining. In fully automated and manless mines, the robots can operate drills in mines (remote connected drilling) and ore carriers (self-driving ore trucks). The autonomous mining systems can be used in harsh, remote, and inaccessible areas (e.g., space and sea floor). Moreover, the robots can work alongside humans as assistants and carry out the mine monitoring and producing mine images.
- Waste utilization. It includes use of mine waste in construction industry and building material (such as tiles, bricks, cement, and pozzolana).
- Biomining. In biomining, the biological agents (e.g., bacteria, virus, and other microbes) are employed in the metals, minerals, and coal extraction process from the ores and rocks. This has become possible because of the recent advancements in the genetic manipulations of microorganisms. These techniques are more energy efficient and produce less pollution.
- Advanced rock fragmentation analyses. Development of new methods to find distribution of fragment size and uniformity index.
- Soil reclamation. It includes rapid development of different types of soils in mine wastes through different methods including vegetation.

8.6 3D Underground Mine Modeling

The underground mine safety threat include falling rocks, suffocation, and explosions. The 3D underground mine models help to improve the safety of miners

and provide easy navigation. These are also utilized to characterize and assess resources, in geochemical mine engineering, groundwater modeling, and geothermal resources, stochastic coupled dynamical systems, and reservoirs. The reliable 3D scans and models can be produced by using different methods such as by using photogrammetry solutions and laser scanner. Modeling and visualization approaches also use virtual reality for training, and in design of engineering systems, and to model fluid flow.

- Photogrammetry systems use high resolution photographs of the mine sites to generate 3D models by using advanced commercial cameras.
- Laser scanners use time of travel of the laser waves (IR pulses) to produce high quality images by using point cloud model at different position and orientation. Laser scanners produce accurate maps and are capable of operating at long-range distances.

8.7 Use of Time-Domain Reflectometry in Mining

The time-domain refractometer is an emerging technology to ascertain ground movements in surface mines, tailings, and underground mines related subsidence. It is also used for subsidence and slant monitoring. It operates by sending EM pulses in transmission line (coaxial cables) and then detecting the reflections resulting from faults. The time of travel of the pulses is used to calculate distance based on the speed of the wave propagation. By using the TDR approach, ground movements can be detected through magnitude and rate of able deformation.

A time-domain reflectometry system with transmission cable is shown in Fig. 8.3. It consists of a pulse generator, oscilloscope, and a sampler. The reflected wave (also shown in Fig. 8.3) is used to determine the properties of the understudy material.

8.7.1 Treatment Technologies for Mining-Influenced Water

The mining-influenced water (MIW) is defined as any water whose chemical composition has been affected by mining or mineral processing and includes acid rock drainage (ARD), neutral and alkaline waters, mineral processing waters, and residual waters. MIW can contain metals, metalloids, and other constituents in concentrations above regulatory standards. The steps involved in mine water treatment process are shown in Fig. 8.4. Some major MIW treatment technologies are shown in Table 8.1.

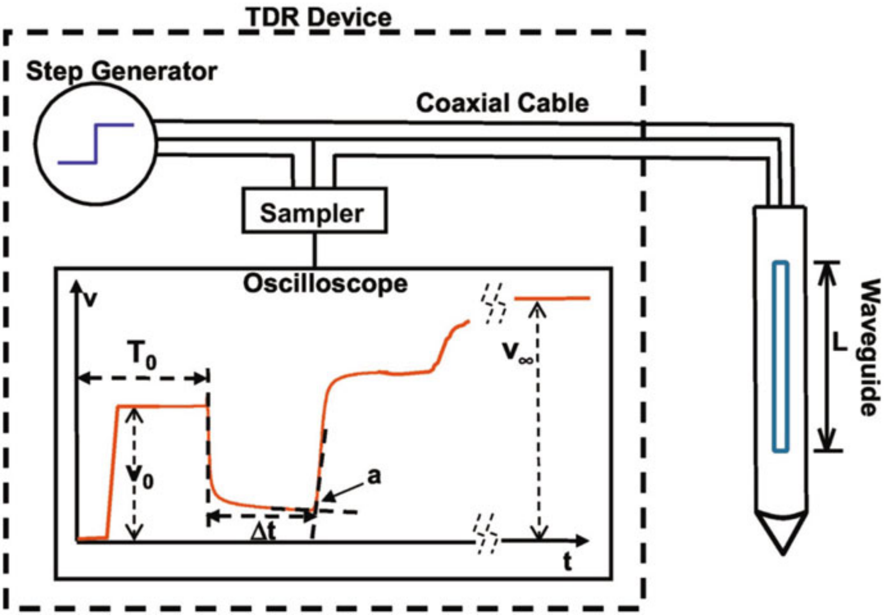

Fig. 8.3 Typical TDR system and waveform of a TDR penetrometer showing travel time determined using the dual-tangent-line method and a constant time offset [7]

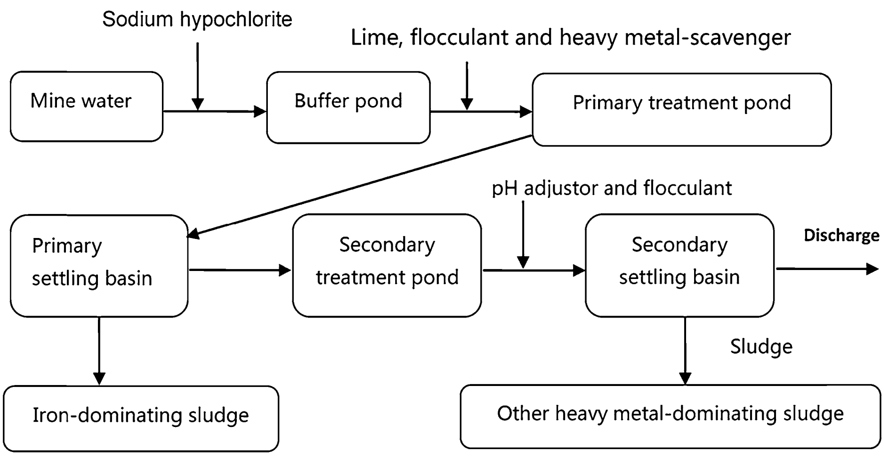

Fig. 8.4 The mine water treatment process. [44]

Table 8.1 The MIW treatment technologies

Technology	Description	Elements treated	Limitations
Electrocoa-gulation	The electrolysis MIW with cathodes and anodes	Arsenic, copper, lead, zinc, total suspended solids, heavy metals, phosphates	High energy consumption
Bioreactors	The contaminants transformation using microorganisms	Selenium, cadmium, copper, nickel, lead, zinc, arsenic, chromium	Large footprint
Aquafix	pH levels raise	Aluminum, copper, iron, manganese, zinc	Iron hydroxides clogging and granular lime accumulation
Nanofiltration membrane technology	Semi-permeable membrane based filtration	Metals, sulfate	Low tolerance levels of membrane
Photoreduction	Ultraviolet light the electron-hole pair generation using ultraviolet light (wavelength of 380 nanometers)	Selenium	Sophisticated equipment
Successive alkalinity producing system	The combined organic substrate and ALD system	Acidity, aluminum, copper, iron, manganese, zinc	Complicated design
Reverse osmosis	Pressure driven separation	Metals, sulfate	Requirements of high operating pressure
Permeable reactive barriers	In situ permeable treatment zone	Trace metals, including: chromium, nickel, lead, uranium, technetium, iron, manganese, selenium, copper, cobalt, cadmium, zinc radionuclides, anion contaminants, including: sulfate, nitrate, phosphate, arsenic various methanes, ethanes, ethenes, propanes, and aromatics	Long treatment periods
Ion exchange	The exchange of contaminant ions with good ions	Metals, hardness	Pre-filtration needed
Fluidized bed reactor (FBR)	The contaminated water is passed through a granular solid media at high enough velocities to suspend or fluidize the media	Selenium, perchlorate, nitrate	High energy requirements
Iron Co-precipitation	A two-step physical adsorption	Selenium, arsenic	High costs
Electrodialysis reversal (EDR)	Electrochemical separation process in which ions are transferred through ion exchange membranes	Arsenic, radium, nitrate, dissolved solids	Sophisticated operation

8.8 Applications of Nanotechnology in Mining

Nanotechnology is a developing field through which unique systems, devices, and materials are created in dimensions of nanometers (1–100 nm). Recently many advancements have been made in the field of biotechnology in mining. Novel nanoscale materials (e.g., dendrimers, nano-tubes, ferritin, metalloporphyrinogens, and silica) are being developed for contaminant adsorption and destruction contaminants through in situ or ex-situ techniques in groundwater remediation. The nano-materials are classified into three different types: (1) nano zero-valent iron (nZVI), (2) bi-metallic nanoscale particles (BNP), and (3) emulsified zero-valent iron (EZVI). There is need to improve the performance and efficiency of these nanoscale materials. The activated carbon (AC) is also being used for in situ remediation of soil and groundwater by using emplacement of AC-based amendments. Moreover, various types of sensors are also being developed using this technology. Furthermore, researchers are working to get insights into the fate and transport of various nanoscale materials in environment, to assess their persistence and toxic impact on different biological systems.

8.9 Mining Site Uncluttering and Restoration

The sustainability mining IoT has a great potential in cleanup and restoration of mining sites by providing characterization tools for this purpose. The characterization of physical and chemical properties of the mine wastes is a complex process. However, by using sensing tools for contamination sensing, the health and environmental impact can mitigated along with selection of proper techniques for restoration and prospective future use of forsaken mine lands.

The mines which are located close to the water sources can release main pollutant of surface water also called abandoned mine drainage (AMD) to lower mines under treatment, hence, causing recontamination, wastage of efforts and resources, restoration delay. Therefore, the proper selection of mine treatment approach is important. The sustainability IoT can benefit from this process of mine cleanup and restoration through its connected, decision support based holistic approach. Accordingly, the watershed contamination caused by these deserted mine lands can be avoided by proper cleanup.

The approaches for mine cleanup and restoration are discussed in the following section. The important mining waste treatment technologies are also discussed.

- Electrokinetics—The electrokinetic remediation (ER) is operated by desorption and elimination of polar organics and metals by applying electrical current electrodes in ground. It is an in situ remediation technology that works in soils, marine dredging, sludge, and mud having low value of permeability. It can treat a wide range of concentrations from few ppm to high ppm. The applications of the electrokinetic method of remediation are shown in Fig. 8.5.

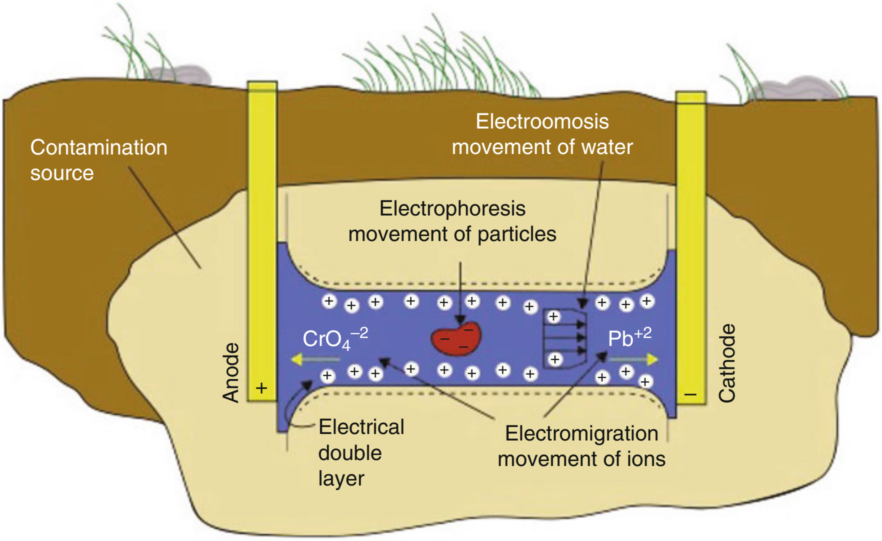

Fig. 8.5 Application of the electrokinetic method of remediation [5]

- Excavation and Disposal. The excavation and disposal process involves removing contaminations by using heavy machinery in tailings, soil, and sediment. This process is generally tailored to the specific site based in the site condition. After the excavation, the targeted treatment techniques are applied to the remaining material. The excavated material is either buried on site in a suitable depository or it is transported off-site for reuse in recycling.
- The process of re-vegetation involves the re-planting and reclaiming the soil of the mines in cleanup and restoration process.
- Soil Amendments. This process involves making amendment to soil by adding nutrients to support re-planting. It revitalizes and enables sustainable plant life development. Different factors are considered such as impact on subsurface, likelihood of leaching to surface waters, and the potential impact on animal and plant life.
- Covering. In covering approach the solid mining wastes are covered to reduce environmental impacts of the waste. It also prevents erosion, harmful dust emissions to the environment, and water contaminant leaking to the surface water.
- Subaqueous Disposal. In this process the contaminated material is removed from the surface and placed in subsurface environment to prevent exposure. It also reduces waste oxidation, acid generation, and release of metals.
- Biosolids. In this approach the nutrient rich biosolids and other organic matter materials are utilized for stabilization, reclamation, and re-vegetation of mine wastes.

- Chemical Stabilization. This ex-situ and in situ treatment approach uses phosphate (phosphoric acid) to reduce the transport of heavy metals. It is considered as the permanent fix to the mine waste.
- Biological Treatment. The biological treatment uses a biological layer to filter metals from the mining-influenced water (MIW).
- Passivation Technologies. In this process the acid-generating materials are passivated by removing contact of sulfide with water and oxygen. This can be achieved by eliminating one of the water, sulfide minerals oxygen, and bacteria.
- It uses plants restoration in tailings, mining solid wastes (MSW), and mining-impacted waters (MIW) and acts as a hydraulic control for drainage.
- Reuse and Reprocessing. After the application of the treatment technologies, the contaminants are removed. Afterwards, the reuse and reprocessing technologies turn the leftover mine waste into environment safe useful products.

8.10 Sensing in Sustainable Mining IoT

The sustainable mining IoT can be used to sense surface and groundwater in mines and geo-technical behavior of tailings as they transition from mineral slurries to soils. Remote sensing including unmanned aerial systems (UAS) and satellite imagery can be used to analyze, assess, monitor, and identify mining activities, water properties, soil contamination, and active geological faults. The sensing technologies for sustainable mining IoT are discussed in this section.

8.10.1 Ore Bodies Sensing

In this section, different approaches for ore bodies sensing are discussed.

8.10.1.1 Underground Gravity Sensing and Rock Mapping

Gravity measurements is a process to locate locating deposits of ore bodies and dense metallic minerals in Earth's crust. Accordingly, the mapping of different ore bodies, types of rocks, and their geological structures is carried out. It can be used to produce density layers at different depths. The gravity and density distribution is impacted by changes in rock strain and stress, relocation due to slides, and water infiltration. A special instrument called the gravimeter is used for gravity sensing. There are two types of the gravity meters: (1) absolute, and (2) relative gravity meter.

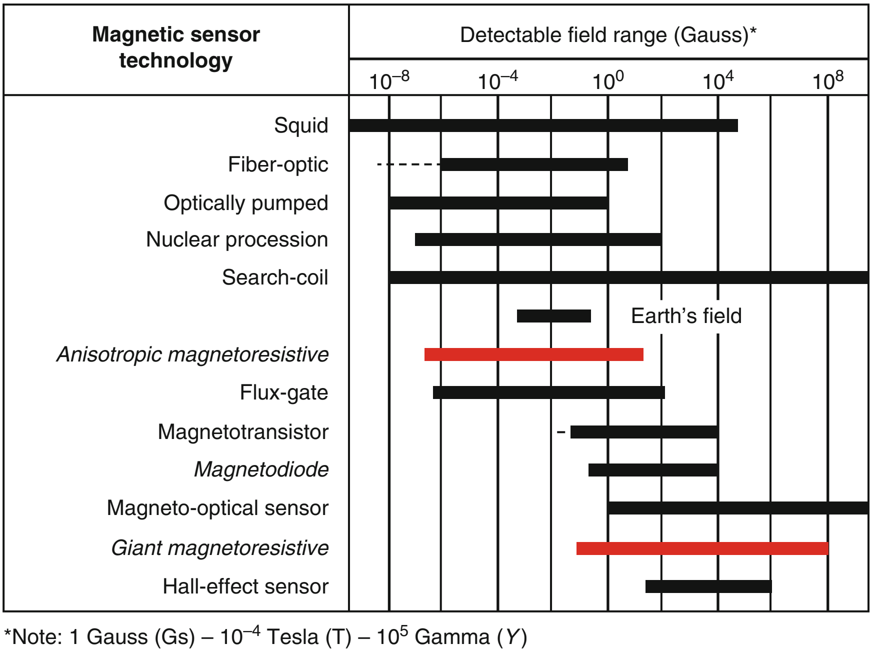

Fig. 8.6 The sensitivity range of various types of magnetometers. [6]

8.10.1.2 Magnetic Sensing

The steel materials, mineral ore deposits, and sedimentary rocks impact the magnetic field of the earth. A magnetic sensing is done to sense and map these changes in the magnetic field of the earth. Many different features of the ores can be mapped (e.g., location, size, and shape). Magnetometers, a very high precision instrument, are used to conduct the magnetic sensing by measuring the magnetic field. The magnetometers use an electric coil as antenna by employing proton rich fluids. When the current is applied, it generates a magnetic field, which causes the polarization of protons. Accordingly, the magnetic flux density is measured. There are two types of magnetometers used for sensing: (1) vector magnetometers, and (2) scalar magnetometers (quantum magnetometers). Magnetic sensing can be done using magnetometers mounted on aircraft. However, the aerial magnetic sensing is challenging due to the height and terrain issues. To overcome this challenge, the backpack mounted Overhauser quantum gradiometer can be used. The sensitivity range of various types of magnetometers is shown in Fig. 8.6.

8.10.1.3 Ground Penetrating Radar Subsurface Sensing

In mining operations the ground penetrating radar (GPR) is widely used sensing/imaging method used to identify underground objects and structures (fractures, joints, and faults) by using radar pulses. GPR operates by transmitting the EM waves to the earth by using one antenna as transmitter and other antenna as a receiver to receive the reflected signal. The bedrock depth in the subsurface environment is obtained using GPR which is then subsequently used for analysis purpose (e.g., planning, texture, and density estimation). Other applications include explorations of minerals, mass stability, grading of deposits, and marking of ore zones.

- Tunneling and Underground Mines. The GPR provide solutions to many of the geological issues (rock mass stability examination, exploitation of mineralogy zones for potash and salt) by providing deep insights into the subsurface environment.
- Placer and Mineral Exploration. The GPS is commonly used in exploration of the iron-rich minerals, diamond and gold fluvial deposits (gold and diamonds) and beach deposits (e.g., titanium) and iron-rich heavy minerals. It is also used to detect and track fault zones, mineral veins, and in nickel exploration.
- Structural Integrity Sensing. The GPR can sense the integrity of the structures to detect cracks and other issues for development and planning purpose.

8.10.1.4 Seismic Sensing

In seismic sensing approach, the shock waves are transmitted through the Earth. The propagation speed of these waves is impacted by the density and other properties of the rocks. These variations in the speed of the wave are used to identify different underground materials. Generally, the transverse, exchange, and longitudinal waves are employed. Different seismic sensing approaches include side-scan sonar, wireless, flip-flop source, and slip sweep.

8.10.1.5 Tomographic Sensing

The tomography is used to measure and visualize the three-dimensional (3D) Earth's reflectivity and velocity distribution, by using multiple transmitters and receivers. Different types of the tomographic sensing are discussed below:

- In transmission tomography, the propagation measurements are done in different type of wireless channels (e.g., surface to borehole, surface to surface, and borehole to borehole). The borehole tomography is used for exploration and identification of underground geological structures and soil profile. A setup for the field experiment is shown in the Fig. 8.7.

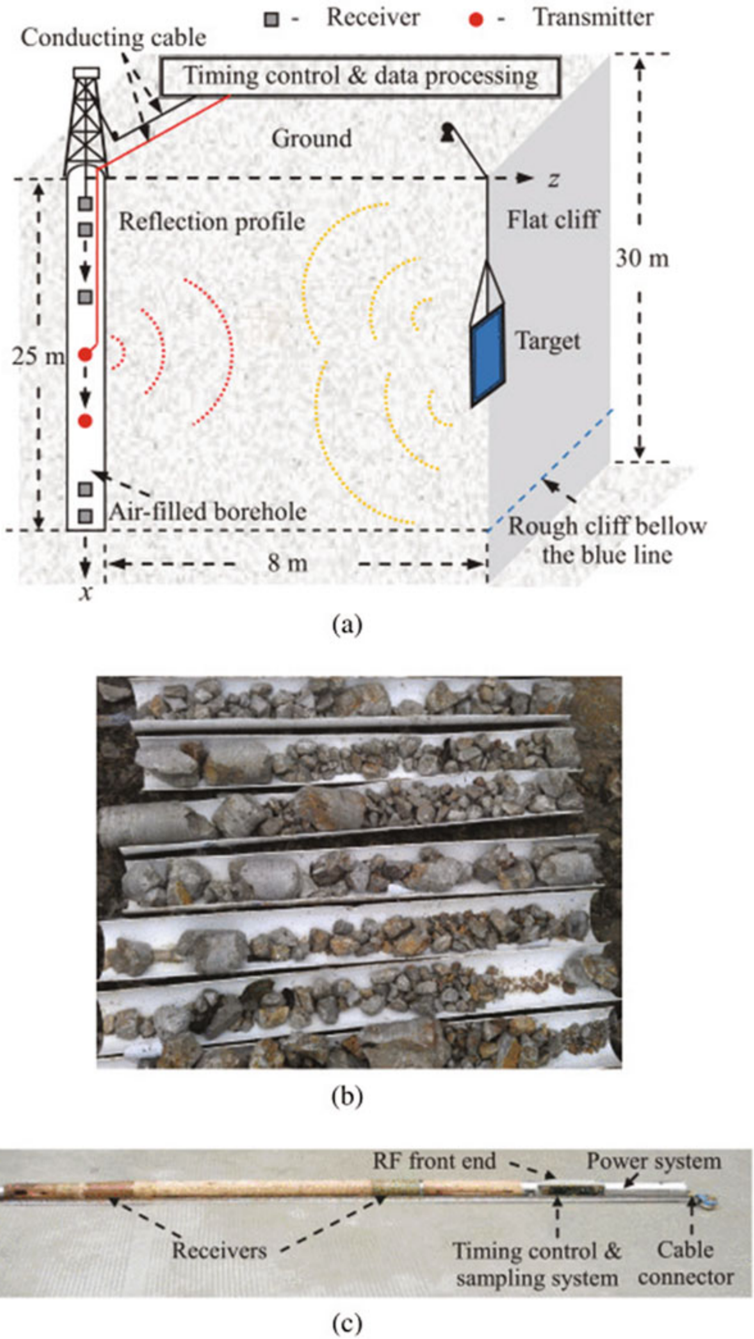

Fig. 8.7 Setup of the field experiment. (**a**) Schematic of the experimental field setup. (**b**) Sample of the surrounding media. (**c**) Subsurface system of the borehole radar [30]

- The reflection tomography is based on the reflection seismology.
- In diffraction tomography, the Fermat's principle is used for analysis instead of Snell's law.

8.10.2 Mine Water Sensing

The groundwater sensing in mining operations is vital to assess the quality and to detect variations in chemical properties of the water both in underground and at point of emission. It is required to ensure compliance with regulatory standards. The water mine sensing can also be used to control the flow and emissions of mine-influenced water (MIW) in and around mining sites.

8.10.3 Remote Sensing

8.10.3.1 Hyperspectral Sensing

Hyperspectral sensing is a remote sensing approach, also known as imaging spectroscopy, and is used to detect and identify minerals. It operates by sensing absorption characteristics which are affected by presence of chemical bonds in a gas, solid, and liquid. A spectrometer is used to distinguish and measure different spectral components. Accordingly, a map or cube representation of the ground surface mineralogy is developed. The accurate hyperspectral sensing depends on the type, resolution, quality, signal-to-noise ratio (SNR) and its wavelength of spectrometer, and the absorption properties of the minerals understudy.

8.10.3.2 Thematic Sensing and Mapping

The Landsat Thematic Mapper is a high resolution multi-spectral mineral scanner with support for spectrum separation. With an opto-mechanical sensor, it provides 30 m resolution with capability to operate in 7 different bands.

8.10.4 Multi-Spectral Scanner

The multi-spectral scanner (MSS) transmits the S-band radio frequency spectrum used for control of the satellite, and so is not affected by the Thematic Mapper's communication difficulties.

8.10.5 Mine Water Contamination Sensors

The pathogens that are found in mine-influenced water and toxic substances present a major sustainability challenge. The detection of these disease-causing substances can be done using chemical and biological sensors. These sensors can be deployed in underwater and underground environments. These sensors operate by using organic transistors and fictionalized gate electrode, where molecularly imprinted polymer (MIP) enables detection of bio-chemical compounds. It can be integrated with sustainability IoT paradigm using wireless communications.

8.10.6 Sensor Technologies for Gas Leaks in Mines

Gas sensors are used to sense gas pressure in mines and play a major role to detect gas leaks in mines. These sensors are characterized based on different parameters which are explained in the following:

- Dynamic Range. Quantity range from low to high concentrations
- Sensitivity. A measure to detect small variations
- Limit of Detection (LOD). Sensing ability to detect lowest quantity (concentration)
- Resolution. A measure to detect smallest variation
- Selectivity. Capacity to different gases
- Response time. Time required from absent to particular quantity
- Linearity. Graphical representation in calibrated values in straight line
- Stability. Time duration to operate for longer time periods

In sustainable mining IoT, gas sensors enable real-time actuation in mines. Many types of sensor technologies for gas leak sensing are discussed in the following.

8.10.6.1 Pellistor Sensor

The combustible gases need a certain temperature for ignition but in catalytic combustion due to certain chemicals the combustion can happen well below the certain temperature. A pellistor is sensor used to sense combustible gases. It has two types: catalytic and thermal conductivity (TC).

- The catalytic sensor is based on glass-covered wire coil catalyst coated wire. When the coil is heated its temperature increases with heat generated from gas burning. Accordingly, the variation in resistance is measured.
- Thermal conductivity sensors are used for sensing based on the thermal conductivity variations of various gases in mines such as hydrogen, helium, and methane, 0%–100% volume.

8.10.6.2 Infrared Gas Sensor

The infrared gas sensing method uses infrared light for combustible hydrocarbon gas. The component of the sensor includes optical IR transmitter, receiver, and a wave length filter. The molecules absorb and emit energy IR waves depending on their properties. The absorbing molecules vibrate more as compared to reflected molecules.

8.10.6.3 Electrochemical Sensors

The electrochemical sensors consist of fuel cells and contain a cathode, an anode, and electrolyte. These are used to detect toxic gases and oxygen. A current is generated due to chemical reaction when the target gas is detected in fuel cell. The produced current represents the volume of the gas and is used for sensing.

8.10.6.4 Semiconductor Sensor

These semiconductor sensors are used for sensing of combustible hydrocarbon gas (CHC) gases. These are manufactured using silicon substrate. The gas being sensed leads to variations in conductivity of the substrate when heated. These sensors have low current leakage and capacitance.

8.10.6.5 Laser Sensor

Different types of the laser sensors are explained in the following:

- Tunable Diode Laser Absorption Spectroscopy. It has two components, (1) tunable diode lasers and (2) laser absorption spectrometer. TDLAS is used to measure gas concentration in methane and water vapor. These receivers sense the wavelength unabsorbed by concentration.
- Differential Sensor (LiDAR). It is based on backscattering wave strength from the concentration and operates in IR, UV, visible wavelengths.

8.10.6.6 Other Gas Sensors

- Fiber Optic Gas Sensor. The fiber optics sensors work on the principle of measuring the wavelength by the absorption of the target analyte.
- Mass Sensor. The Flame Ionization Detector (FID) is used to sense hydrocarbon gas concentration and operates on mass sensing instead of concentration sensing.
- Photoionization Detector. It works by sensing the organic volatile components in UV spectrum by using mobile ion spectrometer technique.

- An array of micro-electro-mechanical sensors (MEMS) on silicon substrate is used to sense different gases.
- Hydrogen Sensor. This works by detection of the resonant frequency due to molecular adsorption.

8.10.7 Autonomous Sensing of Groundwater Quality in Mines

A mining site contains multitude wells which requires the autonomous sensing systems. Therefore, sensing of the quality of the groundwater is of critical importance during mining operations. These sensors system in sustainable mining IoT improves the efficiency of mining operations by data collection and real-time decision making systems. The cloud technology is also useful in mine sensing and automation. Overall, the sustainability mining IoT has the strong potential for beneficial improvements in all areas of mining including machinery monitoring, mine sensing, exploration and mining technology advancement, environmental monitoring, and cleanup and restoration.

8.11 Global Sustainability Efforts

The following organizations are supporting the sustainable mining efforts [37]:

- The American Society of Mining and Reclamation
- The Australasian Institute of Mining and Metallurgy
- The Canadian Institute of Mining, Metallurgy and Petroleum
- The European Federation of Geologists
- The Iberoamerican Association of Mining Education
- The Institute of Geologists of Ireland
- The Peruvian Institute of Mining Engineers
- The Society for Mining, Metallurgy, Resource and Environmental Technology
- The Society of Mining Professors
- The South African Institute of Mining and Metallurgy
- The Spanish Association of Mining Engineers

8.12 Wireless Communications in Sustainable Mining IoT

The importance of the wireless communications in sustainable mining IoT cannot be overemphasized. It provides connectivity among different sensing and monitoring components of the IoT paradigm and enables real-time decision making by integration of different components of the system. The over-the-air (OTA)

wireless communications discussed in Chap. 1 have limited application in some type of mining activities such as underground due to the higher path loss of radio wave propagation in wireless underground communication channel. The higher attenuation as compared to OTA is caused by the complex permittivity of the geological strata, and other multi path components forming from the uneven structure of the mines which block the line of sight (LoS) path. Therefore, empirical channel modeling and impulse response analysis are needed for detailed insights into the physics of radio wave propagation in mines.

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Chapter 9
Internet of Things in Water Management and Treatment

Abstract The goal of the water security IoT chapter is to present a comprehensive and integrated IoT based approach to environmental quality and monitoring by generating new knowledge and innovative approaches that focus on sustainable resource management. Mainly, this chapter focuses on IoT applications in wastewater and stormwater, and the human and environmental consequences of water contaminants and their treatment. The IoT applications using sensors for sewer and stormwater monitoring across networked landscapes, water quality assessment, treatment, and sustainable management are introduced. The studies of rate limitations in biophysical and geochemical processes that support the ecosystem services related to water quality are presented. The applications of IoT solutions based on these discoveries are also discussed.

9.1 Introduction

The survival of humanity depends on the availability of the water resources. The water stress is a major issue due to decreasing freshwater reserves in different regions of the world [2, 20, 23, 53, 89]. The issues of water shortage have exacerbated due to the climate change related variations in frequency and quantity of precipitation [5, 41, 98, 99]. Moreover, the growth in population and emerging human mobility patterns have also contributed to the worsening the issue of shortage. Therefore, the sustainable water resource management and treatment is vital to maintain and conserve the water supply to meet current growth needs and future generations [24]. The water amount and quality interactions impact the water security [33]. The water security is defined as [14, 38, 42]:

> The capacity of a population to safeguard sustainable access to adequate quantities of and acceptable quality water for sustaining livelihoods, human well-being, and socioeconomic development, for ensuring protection against

(continued)

A. Salam, *Internet of Things for Sustainable Community Development*,
Internet of Things, https://doi.org/10.1007/978-3-030-35291-2_9

water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability.

In this chapter, the IoT applications using sensors for waste and stormwater monitoring across networked landscapes in water treatment and sustainable management are presented. The impacts of the human activities on amount and quality of the water are discussed in the next section.

9.1.1 Impacts of the Human Activities on Amount and Quality of Water

The human activities affect the water quantity and quality in different ways [111]. These activities span in various disciplines such as agriculture and forests. The human-induced impacts are discussed below:

- The irrigation water and drinking water withdrawals reduce the stream base flow and surface water table [26]. Accordingly, water temperature, oxygen concentrations are impacted, which lead to rise in summer water temperature, and nutrients concentrations whereby decreasing oxygen concentration.
- Similarly, in agriculture, the tile drainage results in disruptions to natural hydrology by increasing flow and flooding [101]. Accordingly, the wetland water and discharge levels are impacted that lead to increase in nutrients, pesticides, sediments, and reduce soil infiltration and nutrient cycling.
- The impervious surfaces in urban and industrial areas are another factor that impacts the quality and quantity of water. These surfaces are generally covered with impenetrable asphalt or concrete materials. These also cause disruptions natural hydrology and causation of increasing peak flow and flooding [62]. Accordingly, the turbidity and nutrients are impacted which result in an increase in sediments and contaminants which reduce nutrient cycling.
- In forests, the harvesting is done due to many different reasons that increase peak flow and disrupt natural hydrology [63]. The water turbidity, algae, and temperature are impacted. The forest harvesting practice leads to an increase in sediments, nutrients, and pesticides.

Therefore to ensure water security, there is a need for efficient management practices for water sustainability (Fig. 9.1). These water management practices are discussed in the following:

- Source Management. As discussed above, the watershed deterioration, due to agriculture and other land-use practices, accelerates the nutrients and sediments runoff process, which subsequently requires extensive treatment at the receiving end for cleanup operation [19, 102]. In source management, the water supplies

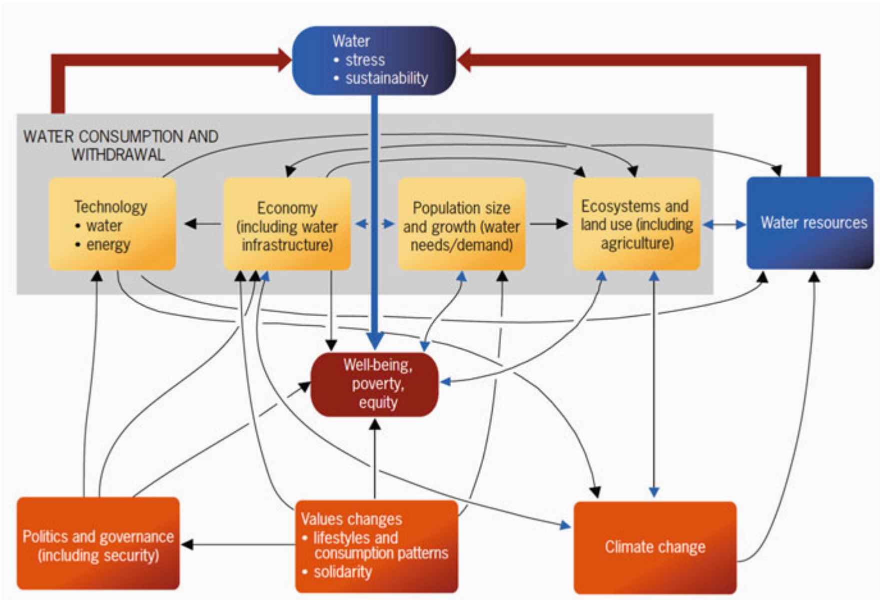

Fig. 9.1 The key factors in water security [34]

are protected at the source, however, the source tracking is a complex and challenging task. Water systems consist of different horological elements in wide geographical areas.

- The purpose-fit management. In this approach the treatment is done based on the end user needs [25].
- Other management practices include conservation, treatment, and reuse, which are discussed in detail later in the chapter.

9.2 Water Management and Treatment using IoT

The water management and treatment using IoT has the potential to overcome these key challenges for sustainable water management [51, 67, 68]. Through its sensing and communication technologies, it can provide useful insights into the sustainable water management approaches by using real-time data and decision support systems for better management and policy decisions. Novel technologies can be developed and connected to the system for water cycle and resource forecasting and understanding the connection between water quantity and land use. The adoption of modern sensing technologies can meet need of water use, quality, quantity sensing, and treatment. Accordingly, the inventory and indicators of the baseline conditions can be developed. It also enables efficient management of water

stresses, pollutants, water data, land use, nutrients, and overflows using wireless communications and remote sensing.

The water management IoT's large scale monitoring of the chemical, physical, and biological properties in different types for water mediums (e.g., groundwater and mine-impacted water) has tremendous potential to inform better treatment options [103]. It is useful for large-scale water contaminant data collection and provides useful insights into the impacts of the contaminant. Accordingly, analytical models can be developed to set limits on contaminant. Moreover, based on the real-time sensing capabilities of the water management using IoT, the health alerts can be issued by the authorities. New techniques for toxin identification and quantification can be integrated into system for performance analysis. Accordingly, the treatment of large areas with high contaminant concentration becomes possible.

Furthermore, the movement of contaminant from watersheds to other water bodies such as rivers, estuaries, and other coastal zones. Moreover, real-time monitoring systems can be developed for in-water HAB [13, 36, 56] observations (such as environmental conditions conducive to HAB) that will aid in rapid species identification and timely mitigation actions. Accordingly, the large-scale empirical studies enabled by the Internet of Things paradigm can inform about the efficiency of different treatment techniques and vulnerable factors. This knowledge is useful to develop new tracking role of different sources (such as wild, human, and animal sources) for microbial contamination. Based on this approach, the combined water organisms can be studied.

It has the potential to establish urban underground infrastructure monitoring stormwater and wastewater overflow monitoring capabilities through integration of subsurface sensing and wireless underground communications [80]. This enables community managers to take timely management actions to control rising water levels which not only cause damage to infrastructure but also lead to community inconvenience. The water management using IoT is also an innovation driver for different sensing technology integration into real-time decision-making, such as in situ sensors, satellite based sensing, and LiDAR, and other in-water sensing methods. Through development of novel sensing techniques, it has also benefits to monitor the post-treatment quality of the water to ensure its safety for human consumption [11, 58, 66, 110].

9.2.1 Water Management and Treatment using IoT

The things in water management and treatment are presented in this section.

- Stormwater, wastewater, gray water, flooding, overflow
- Percolation, precipitation, runoff, flow regimes
- Sediments, nutrients, pesticides
- Water temperature, dissolved oxygen, and turbidity
- Treatment, recycling

9.3 Groundwater Sensing and Treatment

The groundwater is saturated into the pores underground. The groundwater remediation process includes converting the water pollutants into safe content for drinking or altogether eliminating them. Different techniques are used for groundwater treatment such as biological, chemical, and physical treatment methods. These are listed below [57, 60]:

- Excavation/removal
- Pump and treat
- Capping
- Soil vapor extraction (SVE)
- Multi-phase extraction systems (MPE)
- In situ bioremediation
- Air sparging
- Monitored natural attenuation (MNA)
- Vertical engineered barriers (VEB)
- In situ chemical reduction (ISCR)
- In situ thermal treatment

9.3.1 Applications of Nanotechnology in Groundwater Treatment

The nanotechnology is also being applied for remediation of groundwater [29, 97]. In Fig. 9.2, three different approaches of groundwater remediation based on iron particles applications are shown. In this approach, the contaminants in groundwater and dense non-aqueous phase liquid (DNAPL) interacts (physical contact or on being dissolved) with the iron particles for treatment. In Fig. 9.2a, a standard porous reactant barrier fabricated with high quality grainy Fe of the millimeter size is shown. In Fig. 9.2b, an area for reactive treatment is established by serial inoculation of nano-sized iron to develop converging areas of particles for adsorption in the grists of underground water. In Fig. 9.2c, the DNAPL contamination treatment approach by inserting movable nano-size particles is shown. In both Fig. 9.2b and c, the nano-size particles are shown in black, whereas the impacted zones are shown in pink color plumes. Moreover, in Fig. 9.2b there is no particle mobility, and in Fig. 9.2c, the particles are mobile.

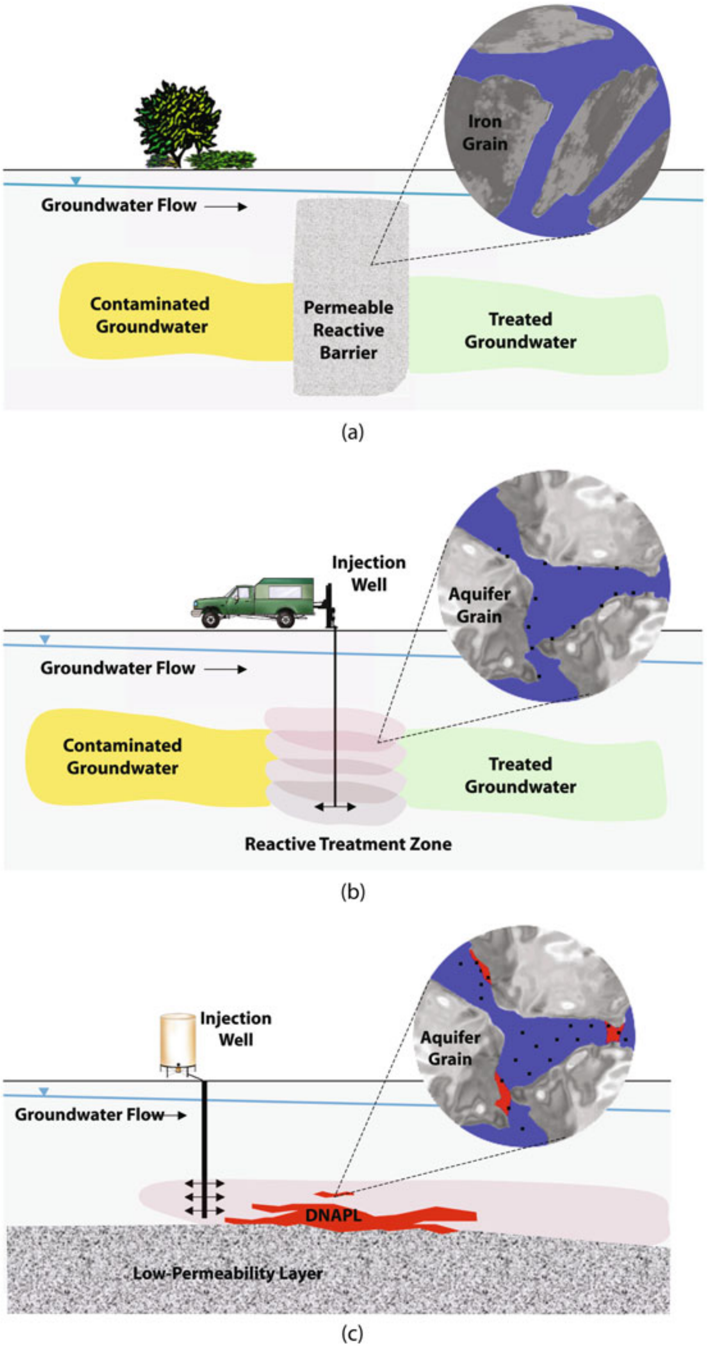

Fig. 9.2 Three approaches to application of Fe particles for groundwater remediation: (**a**) an area for reactive treatment is established by serial inoculation of nano-size iron to develop converging areas of particles for adsorption in the grists of underground water, (**b**) a 'reactive treatment zone' formed by sequential injection of nanosized Fe to form overlapping zones of particles adsorbed to the grains of native aquifer material, and (**c**) DNAPL contamination treatment approach by inserting movable nano-size particles [97]

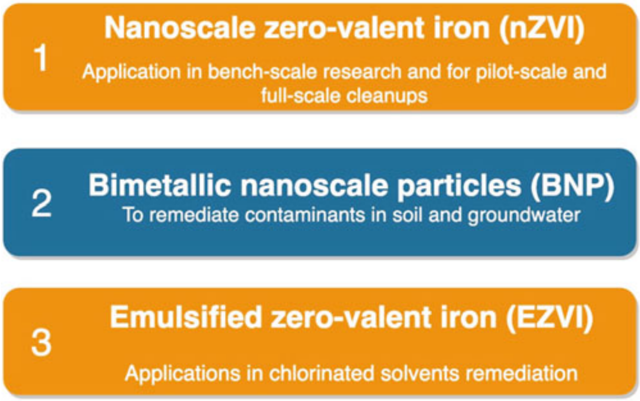

Fig. 9.3 Types of nanomaterials with their contaminant remediation capabilities

9.3.2 The Nanomaterials for Contaminant Remediation

Several types of nanomaterials have been used for the remediation of contaminants such as chloroethene, trichloroethylene (TCE), Tetrachloroethylene, and 1,2-dichloroethane (DCA). Various types of nanomaterials with their remediation capabilities are shown in Fig. 9.3. The nZVI are utilized in water treatment due to their elevated surface reactivity [52]. The iron particles (BNPs) are employed in groundwater by using the oxidation reduction reaction process in order to attain contaminant degradation. The EZVI are used to treat human carcinogen chlorinated hydrocarbons.

9.3.3 Hazardous Water Sensing and Treatment

The technologies for hazardous waste cleanup are discussed in the following. These contaminant can be found in different medias such as surface water, soil gas, soil, sediment, light non-aqueous phase liquid (LNAPL), groundwater, fractured bedrock, and dense non-aqueous phase liquid (DNAPL) [31].

- Phytotechnology. In this water and soil treatment technology, different types of plants are used to debase, remove, restrain, and disable contaminants [31].
- In situ chemical oxidation. In this approach, various oxidants are inserted in the underground environment to transform the contaminant into immobile components such CO_2 and CI−. This technology is very effective in treatment of non-aqueous phase liquids (NAPL) [31, 100].
- In situ flushing. In this soil and groundwater treatment technique, the flushing solutions (e.g., cyclodextrin, cosolvents, surfactants, oxidants, and chelants) are

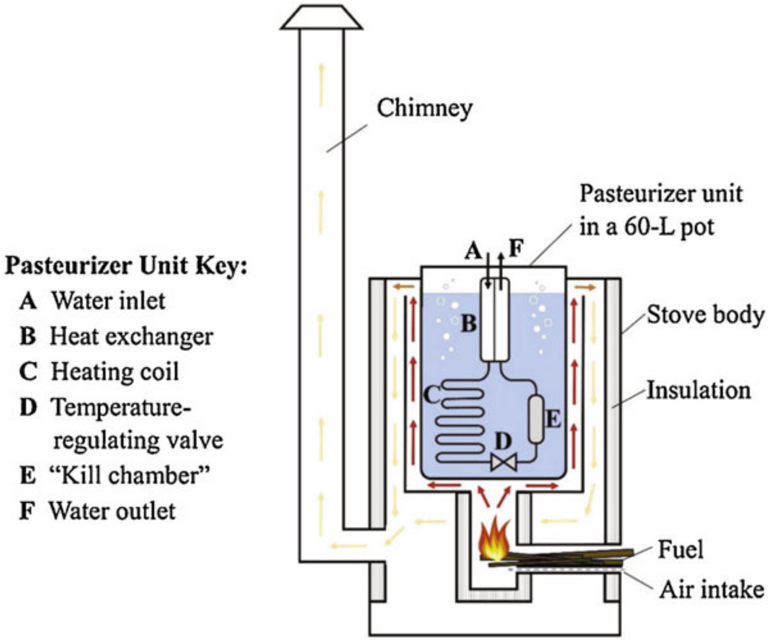

Fig. 9.4 A self-regulating biomass-powered system designed to heat water to the pasteurization temperature [22]

injected into the contamination areas to make contaminants either mobile or soluble. Accordingly, the mixed solution is treated either in situ or through extraction. The contaminants receptive to this type of treatment includes polychlorinated biphenyls (PCB), NAPLs, volatile organic compounds (VOC) and semi-VOCs, cyanides, pesticides, dioxins, metals, corrosives, and radioactive components [65].

- Heating Technologies. These are based on contaminants treatment by heating of water and underground environment using different heating techniques (e.g., conductive, electrical resistive, RF, steam, and hot air injection). These are used in PCB, polychlorinated, oil contaminants, and chlorinated solvents [47, 112] (Fig. 9.4).

9.4 Underground Communications in Urban Underground Infrastructure Monitoring

In this section, the path loss analysis of wireless underground communications in urban underground IoT for wastewater monitoring has been presented. The potential of wireless underground technology and sensor solutions in different transformative

urban underground IoT applications (e.g., real-time flow monitoring, intrusion and infiltration (I&I) isolation, and smart manhole lids) is explored. The path loss model evaluations are done in different communication media under different layers thickness levels. The design of sewer and stormwater overflow monitoring systems can benefit from these findings.

9.4.1 Wastewater and Stormwater Monitoring Needs

Urban areas have public infrastructure worth billions of dollars located underground. City governments spend significant budget annually to support this underground infrastructure. The underground IoT solutions are rare due to challenges in connectivity and needs for extensive cabling to leverage over-the-air communication solutions, which increases costs. By combining wireless underground technology and sensor solutions [50, 106], many transformative urban underground IoT application such as real-time flow monitoring, intrusion and infiltration (I&I) isolation, and smart manhole lids can be developed.

The city wastewater bodies are responsible for collecting and treating wastewater at wastewater recovery facilities by processing many million gallons a day [49]. Cities have a strong need to monitor the quantity and quality of wastewater entering the collection system and reaching these recovery facilities [8, 10, 15, 28, 88]. Extra quantities of water entering the pipes can cause backups that result in sanitary sewer overflows [35, 59]. Eliminating I&I is important for controlling the flow of extraneous water into the pipeline [35, 95]. However, currently most cities do not have access to affordable underground sensor and connectivity technologies designed to detect problems in time to take preventive action. In this paper, we present the path loss analysis of wireless underground communications using urban underground IoT for wastewater monitoring [46, 90]. The architecture of urban underground IoT for wastewater monitoring is shown in Fig. 9.5. It shows different component of the system (e.g., base station, catch basin, UG transmitter and receiver, and drainage system). A storm drain is a major component of the drainage system and served as inlet and outlet for the runoff. Accordingly, it discharges the runoff to a water body (river, stream, channel, or creek).

The wastewater flow monitoring application can utilize wireless underground communication technology [104], which allows IoT radios to be buried underground [30]. Underground pipe monitoring sensors, connected to wireless underground software defined radios, can wirelessly connect to the roadside urban infrastructure at the nearest traffic light pole. This wireless underground technology has been shown to be successful in agricultural fields for several years with effective communication ranges of 100–200 m [106]. We present a theoretical path loss analysis for wireless underground communication through asphalt to design long-range wireless communication radios, which will allow underground radios to be deployed sufficiently deep to keep cabling to the underground pipes at a minimum while maintaining connectivity [9, 81, 86]. Providing this information to mobile

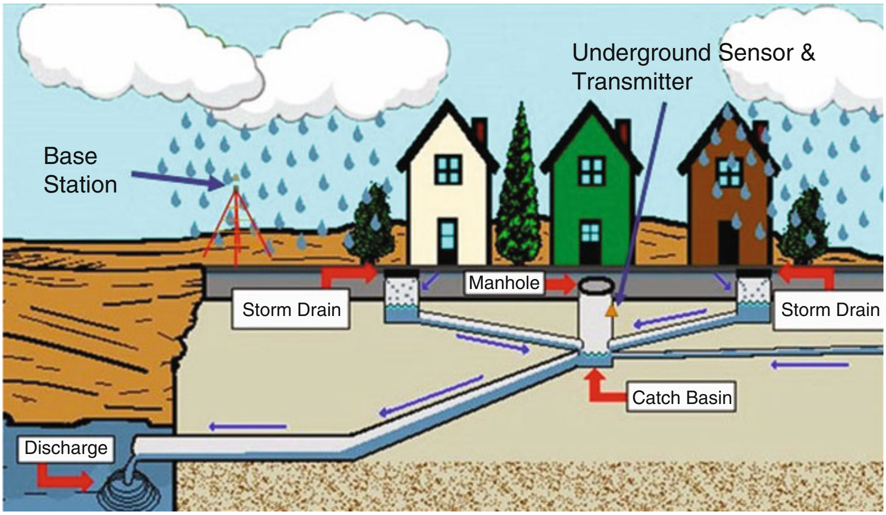

Fig. 9.5 The architecture of urban underground IoT for wastewater monitoring [80]

devices will enable large-scale dissemination of timely alerts during emergencies. This application can also drive realistic wireless traffic for evaluating solutions for wireless underground networks.

9.4.2 Internet of Underground Things for Wastewater and Stormwater Monitoring

Internet of Underground Things (IOUT) has numerous applications in the field of digital agriculture [3, 18, 30, 39, 54, 70–79, 81–85, 87, 94, 96]. Another important application is in the area of border monitoring, where this technology is being employed for border enforcement and to curtail infiltration [4, 93]. Moreover, IOUT is also being utilized for landslide and pipeline monitoring [39, 91, 92].

The IOUT delivers consistent access to data garnered from the farming areas via underground networking, aboveground networks, and the Internet. IOUT incorporates in situ underground sensing [1] of soil physical, chemical, and biological factors which includes water content sensing, salinity sensing, pH and nitrogen sensing, and temperature sensing. It also has the communication capabilities built-in as one of the integral component to provide the sensing data from the plants, roots, and soil. Moreover, it has the ability to include the environmental sensing capability to provide the real-time data pertaining to the diverse environmental phenomena such as wind data, rain information, and solar potential [107]. When integrated with agricultural machinery and farm equipment on the field (e.g., seeding equipment, irrigation controllers, harvesting machines and combines), the IOUT leads to the full self-sufficiency on the smart farming fields, and has the strong potential of

development of enhanced food production solutions and applications in the area of digital agriculture [106]. The IOUT is also being utilized to provide useful decision-making information to the growers in the field in real-time.

In Sect. 9.4.4, the model evaluations are performed using different parameters.

9.4.3 Path Loss Model for Stratified Media to Air Communications

In this section we present the attenuation in the stratified medium and dispersion of subgrade of soil.

9.4.3.1 Attenuation in the Stratified Medium

The layered structure of the underground medium is shown in Fig. 9.2. The distinctive properties of wave transmission in the stratified medium need expressions of the path loss by taking into account the characteristics of different layers involved in the wireless communications [108].

Free Space Path Loss
From Friis equation [37], the received transmission power in over the air medium (OTA) at the transmitter-receiver (TR) communication path r from the transmitting antenna can be expressed by using the logarithmic scale as:

$$P_r = P_t + G_r + G_t - L_{fs}, \tag{9.1}$$

where the transmission power of the transmitter is P_t, the antenna gains of the transmitting and receiving antennas are expressed as G_r and G_t, and L_{fs} is over the-air-path as exhibited in the free space (expressed in dB), and it is written as:

$$L_{fs} = 33.2 + 20\log(d) + 20\log(f), \tag{9.2}$$

where the length of total transmission path (e.g., the distance between the transmission and the receiver antenna expressed in meters) is denoted by d; and the frequency of the operation of the communication system is expressed as f with unit in MHz.

We consider transmission loss at two levels: (1) free space path loss, (2) loss through stratified layers.

Propagation Loss in the Layered Medium
For the propagation through layered medium, loss through medium should account for the effect of the properties of different layers involved in communication. Accordingly, the strength of the signal received at the receiver can be rewritten as [105]:

$$P_r = -L_m + G_r + P_t + G_t, \tag{9.3}$$

where $L_m = L_{fs} + L_l$, and L_l denotes the extra signal attenuation exhibited by the transmission of EM waves through the stratified medium, which is ascertained by taking into account the existing dissimilarities of EM wave propagation occurring in the layered medium in comparison to that of the free space. The extra prorogation wave loss, L_l, in the stratified medium, hence, consists of accumulative loss occurring in total number of layered medium through which wireless communications is carried out:

$$L_l = \sum_{n=0}^{N-1} L_n, \tag{9.4}$$

where L_n is the attenuation loss in the nth layer for each of the N layers.

The transmission loss exhibited in a particular layer denoted as L_n, is mainly dependent on the di-electric permittivity, and the wavenumber of the medium in that particular layer, that can be expressed as $j\beta + \alpha = \gamma$ given as:

$$\alpha = \omega\sqrt{\frac{\mu\epsilon'}{2}\left[\sqrt{1 + (\frac{\epsilon''}{\epsilon'})^2} - 1\right]}, \tag{9.5}$$

$$\beta = \omega\sqrt{\frac{\mu\epsilon'}{2}\left[\sqrt{1 + (\frac{\epsilon''}{\epsilon'})^2} + 1\right]}, \tag{9.6}$$

where the ω, which is equivalent to the $2\pi f$, denotes the angulated spectrum of the frequency, the magnetized permeableness is expressed as the μ, the imaginary and real components of the permittivity of the material are denoted as ϵ'' and ϵ', respectively, (9.9). Consequently, the propagation loss, L_n, for a particular layer in the stratified medium is found as [48]:

$$L_n[dB] = 20 \cdot \gamma \cdot d \cdot \log 10(e), \tag{9.7}$$

where $e = 2.71828$, and d is thickness of the nth layer.

It can be seen that the propagation loss depends on the complex dielectric permittivity of the electromagnetic wave propagation in medium, layer thickness d, operating frequency, f, and other properties of the medium. Next, we consider the dispersion of next layer involved in the sewer overflow monitoring system.

9.4.3.2 Dispersion in Different Subsurface Layers

The ability of the materials in different subsurface layers to holdout against the applied electric charge defines its permittivity. The permittivity also depends on the electromagnetic absorption potential of the material. With the oscillation electric field, the charge flows and results in two charge components of the current (e.g., charging and loss). The heat loss represents the dissipated energy into the thermal excitation. The polarization of the soil and asphalt material in the subsurface layers

is coupled with the dielectric properties and can be divided into dipolar, atomic, and electric types. It also depends on the frequency because the dielectric displacement and polarization response are different at different carriers. In the following, we discuss dispersion of materials involved in the subsurface layers. The material permittivity prediction expressions are presented.

9.4.3.3 Dispersion of Subgrade of the Soil Medium

By employing the findings of an extensive empirical campaign on soil permittivity [61], the permittivity spectra of the medium in the frequency range of 300 to 1300 MHz can be determined as shown in the following:

$$\epsilon_s = -j\epsilon_s'' + \epsilon_s', \tag{9.8}$$

$$\epsilon_s' = 1.15\left[1 + \frac{\rho_b}{\rho_s}\left(\epsilon_s^{\alpha'}\right) + m_v^{\beta'}\epsilon_{f_w}^{\prime\alpha'} - m_v\right]^{1/\alpha'}$$
$$-0.69, \quad \epsilon_s'' = \left[m_v^{\beta''}\epsilon_{f_w}^{\prime\prime\alpha'}\right]^{1/\alpha'}, \tag{9.9}$$

where the relative complex dielectric permittivity of the soil medium is denoted by ϵ_s, the m_v is used to express the measure of the volumetric water content present in the medium, the bulk density is ρ_b that is the indicator of the compaction of the soil material with unit of g/cm^3 and is used in relation to the solid soil particles ρ_s which is 2.65 g/cm^3. The value of the α' is 0.65. The value of other soil dependent experimentally determined constants β'' and β' is given as:

$$-0.52S + 1.28 - 0.16C = \beta', \tag{9.10}$$

$$-0.61S + 1.34 - 0.17C = \beta'', \tag{9.11}$$

where the amount of sand particles present in the soil is denoted by S, and contents of the clay particles found in soil is expressed as C. The relative dielectric permittivity of the free water (both the imaginary and real components) are represented by $\epsilon' f_w$ and $\epsilon'' f_w$.

9.4.3.4 Dispersion of Asphalt

Since, the medium of communications in sewer overflow monitoring application is multi-layer structure, hence, it is important to determine the dielectric value of asphalt layer (top surface in Fig. 9.6). The formula is given as:

$$\epsilon' = \frac{3}{4\pi}\frac{\epsilon_0 - 1}{\epsilon_0 + 2}. \tag{9.12}$$

Fig. 9.6 The layered structure of the underground medium [80]

It should be noted that when the frequency is increased the value of dielectric constant of asphalt also increases. The impact of dependency of the dielectric constant on the frequency is caused by dipolar polarization (e.g., the disassociation molecule charges). The asphalt substance (bitumen) contains many aromatic and asphaltene molecules. Accordingly, it also depends on the applied electric field.

9.4.3.5 Dispersion of Base Gravel Aggregate

The base gravel aggregate layers are comprised of different materials such as of stones, sand, pebble, and air voids in less organized fashion. Because of this semi-random organization, the dispersion in these layers depends on the size of particles and wavelength. The effective permittivity of the gravel aggregate (consisting of a layer in which rock particles, sand particles, pebbles, and air voids with diverse dispersion properties are arranged together) is determined as:

$$j\frac{\epsilon_0 - 1}{\epsilon_0 + 2\epsilon'}, \tag{9.13}$$

where j is the percentage of the solid material in the volume.

9.4.4 *Model Evaluations*

In this section, we present the path loss analysis. The model parameters considered for this evaluation are shown in Table 9.1. The soil and asphalt layer thickness are 20 and 10 cm, respectively, with soil moisture level of 5%. The operation frequency of 433 MHz is used with transmission power of 20 dBm. In Fig. 9.3, the propagation loss in the asphalt medium with change in layer thickness has been shown. It can be

Table 9.1 Model evaluation parameters [80]

Parameter	Value
P_t	20 dBm
Thickness of the soil layer	20 cm
Thickness of the asphalt layer	10 cm
Frequency	433 MHz
Noise floor	−90 dBm
Soil moisture	5% by Volume
Asphalt temperature	300 K/80.33 F/26 C

observed that with layer thickness of less than 1 m, the propagation loss is less than 5 dB. However, it increases with increase in layer thickness. It increases to 15 dB for the 4 m thick asphalt layer.

The path loss with change in distance is shown in Fig. 9.4. It can be observed that for communication distances up to 4 km, the path loss is less than 100 dB. It increases to 107 dB for a distance of 10 km. The received signal strength indicator (RSSI) with distance is shown in Fig. 9.5. It can be observed that the RSSI decreases with distance. This decrease is abrupt for distances less than 2 km. Afterwards, it decreases gradually. At communication distance of 4 km, the −80 dBm RSSI indicates that underground nodes in urban underground infrastructure monitoring IoT can effectively communicate with urban roadside wireless communication infrastructure.

In Fig. 9.6, the propagation loss in the soil medium with change in layer thickness has been shown. It can be observed that with layer thickness of less than 2 m, the propagation loss is less than 37 dB. However, it increases with increase in thickness. It increases to 57 dB for the 4 m thick soil layer. Moreover, it can also be observed that soil medium has higher loss as compared to the asphalt medium. This is caused by the higher permittivity of the soil as compared to the asphalt. The higher water holding capacity of the soil in comparison to asphalt medium leads to the higher permittivity of soil.

The effect of temperature change on propagation loss in asphalt is shown in Fig. 9.7. It can be observed that with change in asphalt temperature from 300 K to 360 K, the path loss increases to 3.6 dB. Therefore, the wireless communication system in urban underground infrastructure monitoring IoT should be designed by considering the temperature change of the asphalt medium in different weather conditions (Figs. 9.8 and 9.9).

9.5 Sensing and Sampling

In this section, different sensing related to water sampling needs are discussed. First the contaminant sensing is discussed (Figs. 9.10 and 9.11).

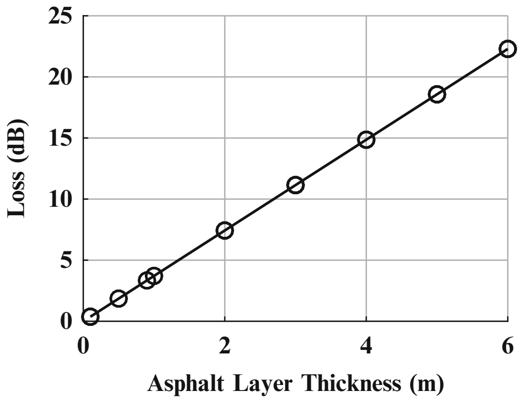

Fig. 9.7 The propagation loss in the asphalt medium with change in layer thickness [80]

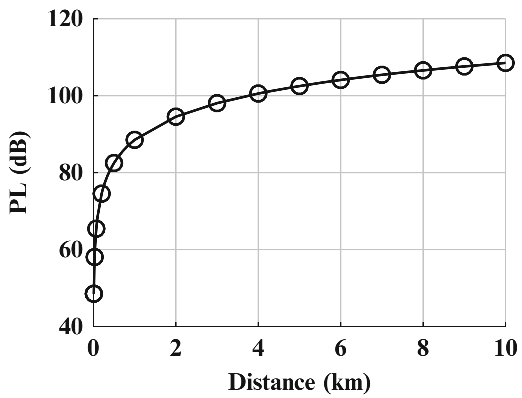

Fig. 9.8 The path loss with change in distance

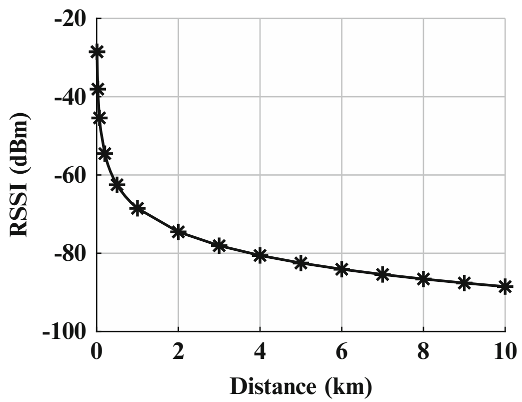

Fig. 9.9 The received signal strength indicator with distance [80]

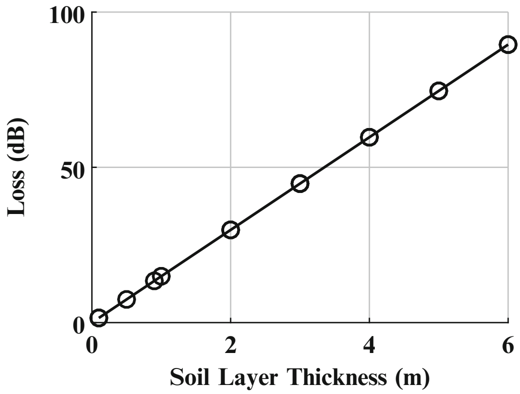

Fig. 9.10 The propagation loss in the soil medium with change in layer thickness [80]

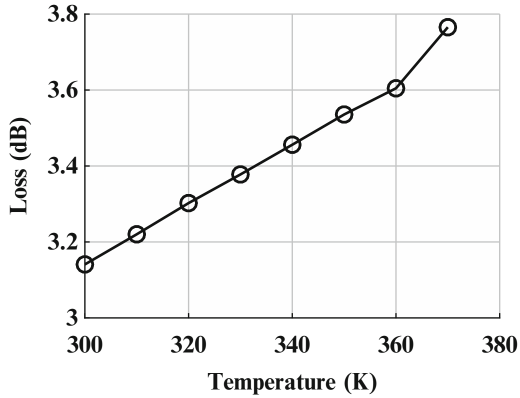

Fig. 9.11 The effect of temperature change on propagation loss in asphalt [80]

9.5.1 Contaminant Sensing

The contaminant sensing is not only important to detect the contaminants but it is also useful to assess the extent and nature of contaminants. The different contaminants in need of sensing are shown in Fig. 9.12.

9.5.2 Sensing for Wastewater Treatment and Reuse

Another important source of water supply is wastewater reuse, where water from different sources (e.g., industry, agriculture, and domestic) is collected, treated, and recycled to mitigate its detrimental impacts using multi-phase chemical, mechanical, and biological processes. The wastewater systems are also impacted by climate change [7, 27, 32]. Currently, the hazardous health environmental and health impacts of wastewater include its mixing with groundwater and surface water. Moreover, the health impacts resulting from consumption of this reclaimed water needs more investigation. Moreover, the advanced methods for removal of

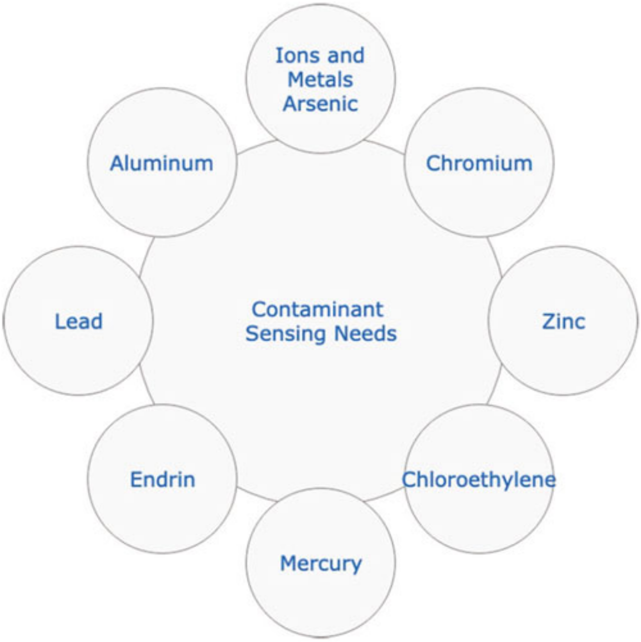

Fig. 9.12 The sensing needs for different contaminants

bacteria, analytes, their genes, micro-pollutants, byproducts, and residual materials are needed. A summary of site monitoring and characterization techniques for water is given below [31]:

- Anodic stripping voltammetry (ASV)
- Biosensors
- Colorimetric test kits
- Direct reading probes
- Electro-optical sensors
- Fiber optic chemical sensors (FOCS)
- Fourier Transform Infrared Spectroscopy (FTIR)
- Fuel Fluorescence Detector (FFD)
- GC-ion Mobility Spectrometry (IMS)
- Gas Chromatography (GC)
- Gas Chromatography/Mass Spectrometry (GC/MS)
- Graphite Furnace Atomic Absorption Spectrometry (GFAA)
- Gross counters
- Immunoassay test kits
- Inductively Coupled Plasma Spectrophotometry (ICP)
- Ion Selective Electrodes (ISE)
- Liquid Chromatography (LC)

- Membrane Interface Probes
- Mercury vapor analyzers
- Surface Acoustic Wave Sensors (SAWS)
- Ultraviolet fluorescence (UVF) test kits

9.5.3 Agricultural Hazards Sensing

The agriculture is becoming exceedingly vulnerable to the soil degradation, water scarcity, deteriorating mountain ecosystems, and more variable and intense weather patterns (e.g., floods, drought, frosts). However, there are major gaps in our understanding of changes in agriculture and how these changes will affect agriculture. Improved knowledge needs to be acquired to anticipate, plan, and adapt to these changes and to gain new grounds in agriculture. Furthermore, efforts are needed to develop better detection techniques for per- and poly-fluoroalkyl substances (PFAS), and PFAS-containing waste found in different soils. Among existing techniques, granular activated carbon (GAC) is a growing technology in PFAS treatment in water [17, 69]. However, there is a significant lack of data and procedure development in terms of fundamental understanding and quantification of medium properties. The adsorptive and destructive technologies are considered for both soils and waters [12, 21]. Other remediation approaches are anion-exchange, ozofractionation, chemical oxidation, electrochemical oxidation, sonolysis, soils stabilization, and thermal technologies [6, 45, 55, 64]. These treatment technologies are not best suited to provide PFAS management systems with almost real-time sensing data to facilitate fast decision-making [40, 44].

To meet the need of practical approaches to manage the potential environmental impacts of PFAS, environmental researchers must develop and implement new technologies to enhance detection and control of PFAS with fewer inputs. Enhanced techniques that are more practical and efficient in control, treatment, destruction, and removal of PFAS in soils are needed. This complex and arduous task requires interdisciplinary endeavors that combine various environmental science disciplines to develop such tools and implement them in the field to achieve this purpose. A summary of site monitoring and characterization techniques for soil is given below [31]:

- Colorimetric test kits. Test kits are self-contained analytical kits that generally use a chemical reaction that produces color to identify contaminants, both qualitatively and quantitatively [43].
- Fiber optic chemical sensors (FOCS). Fiber optic chemical sensors (FOCS) operate by transporting light by wavelength or intensity to provide information about analytes in the environment surrounding the sensor. The environment surrounding a FOCS is usually air or water. FOCS can be categorized as intrinsic or extrinsic. Extrinsic FOCS simply use an optical fiber to transport [109].

- Gas Chromatography (GC). Chromatography is the science of separation which uses a diverse group of methods to separate closely related components of complex mixtures. During gas chromatographic separation, the sample is transported via an inert gas called the mobile phase [16].
- Gas Chromatography/Mass Spectrometry (GC/MS). Mass spectrometry (MS) is an established analytical technique that identifies organic compounds by measuring the mass (more correctly, mass to charge ratio) of the compound's molecule. Mass spectrometry is noteworthy among analytical techniques because the signals produced by a spectrometer are the direct result of chemical reactions such as ionization and fragmentation, rather than energy state changes that are typical of most other spectroscopic techniques.
- Laser-induced Fluorescence (LIF). Laser-induced fluorescence (LIF) is a method for real-time, in situ field screening of residual and non-aqueous phase organic contaminants in undisturbed vadose, capillary fringe, and saturated subsurface soils and groundwater.
- Membrane Interface Probes. A MIP is a semi-quantitative, field screening device that can detect volatile organic compounds (VOCs) in soil and sediment. It is used in conjunction with a direct push platform (DPP), such as a cone penetrometer testing rig (CPT) or a rig that uses a hydraulic or pneumatic hammer to drive the MIP to the depth of interest to collect samples of vaporized compounds.
- X-ray fluorescence (XRF). XRF instruments are field-portable or handheld devices for simultaneously measuring metals and other elements in various media.
- Direct reading probes
- Downhole pyrolysis explosives sensor
- Electromagnetic induction (EM)
- Fourier Transform Infrared Spectroscopy (FTIR)
- Fuel Fluorescence Detector (FFD)
- GC-ion Mobility Spectrometry (IMS)
- Graphite Furnace Atomic Absorption Spectrometry (GFAA)
- Gross counters
- Ground Penetrating Radar (GPR)
- Immunoassay test kits
- Inductively Coupled Plasma Spectrophotometry (ICP)
- Ion Selective Electrodes (ISE)
- Laser-induced Breakdown Spectroscopy (LIBS)
- Liquid Chromatography (LC)
- Magnetometry
- Mercury vapor analyzers
- Seismic reflection/refraction
- Soil/sediment micro-heterogeneity management to improve data precision
- Surface Acoustic Wave Sensors (SAWS)
- Ultraviolet fluorescence (UVF) test kits

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Chapter 10
Internet of Things for Sustainability: Perspectives in Privacy, Cybersecurity, and Future Trends

Abstract In the sustainability IoT, the cybersecurity risks to things, sensors, and monitoring systems are distinct from the conventional networking systems in many aspects. The interaction of sustainability IoT with the physical world phenomena (e.g., weather, climate, water, and oceans) is mostly not found in the modern information technology systems. Accordingly, actuation, the ability of these devices to make changes in real world based on sensing and monitoring, requires special consideration in terms of privacy and security. Moreover, the energy efficiency, safety, power, performance requirements of these device distinguish them from conventional computers systems. In this chapter, the cybersecurity approaches towards sustainability IoT are discussed in detail. The sustainability IoT risk categorization, risk mitigation goals, and implementation aspects are analyzed. The openness paradox and data dichotomy between privacy and sharing is analyzed. Accordingly, the IoT technology and security standard developments activities are highlighted. The perspectives on opportunities and challenges in IoT for sustainability are given. Finally, the chapter concludes with a discussion of sustainability IoT cybersecurity case studies.

10.1 Introduction

The cybersecurity in Internet of Things for sustainability is the process of protecting the systems, sensors, and wireless communications from digital attacks [25]. It is important to ensure that the sustainable IoT paradigm will operate in safe and secure environment to achieve sustainability goals using systems which are dependable, reliable, and trustworthy [10, 29, 33]. In many of the sustainability IoT paradigms discussed in this book, the cybersecurity risks to sensors and monitoring systems are different from the conventional networking systems in many aspects:

- The interaction of sustainability IoT with the physical world phenomena (weather, climate, water, and oceans) is generally not found in the modern information technology systems. Accordingly, the actuation (ability of these devices to make changes in real world) based on sensing and monitoring, requires

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special consideration in terms of privacy and security. Moreover, the energy efficiency, safety, power, performance requirements of these device distinguish them from computers [89].

- The scale of IoT for sustainable community development expands beyond cities, to the global scale including oceans, climate, and water monitoring applications. Hence, diverse mediums of communications are involved (e.g., satellite, terrestrial air, cellular, and wide area networks) [90].
- Unlike server farms, various sustainability IoT are envisaged to function in harsh and challenged environment for prolonged periods of time without little or no physical access. Accordingly, unconventional security concerns emerge regarding remote access and data privacy [2, 101].
- Lack of upgrade and patching due to high cost is a major challenge as compared to conventional systems [58].
- The sensing data in some of the sustainability paradigms takes longer time to accumulate (such as in climate and agriculture), thereby, presenting prolonged exposure related security challenges [80, 81].
- The implementation of the security features on these sustainability IoT devices requires well-thought design keeping in view its integration in the holistic paradigm and novel insights (security by design) and innovations into the potential risks that can comprise information [33, 43].

In IoT for sustainable community development, it is vital to recognize that sustainability things do not function in a vacuum, rather these are part of the entire ecosystem. Therefore, instead of the individual based security, the holistic approach is of utmost importance. The holistic approach should take end-to-end strategy for cybersecurity across the entire sustainability landscape [33, 54]. Moreover, within each sustainability paradigm, each system has its own specific function and purpose with its ability to tolerate risks. Hence, no single cybersecurity protocol or set of rules can be applied to entire paradigm. These risk mitigation approaches vary based on system needs, functions, and use cases.

Accordingly, it is import to underscore the characterization of risk-based insights into functionality, deployment environment, set of behavior and applicabilities and their integration into the paradigm [7]. In this regard, the outcome based cybersecurity approach can be applied where the final outcome becomes more important as compared to less significant means to achieve those outcomes. The examples of weaknesses and unreasonable cybersecurity approaches towards sustainability IoT are discussed in the following [44, 53].

- Data and information storage in plain text
- Negligence in adequate policy implementation
- Oversight of in fixing current vulnerabilities
- Failure to utilize proper cybersecurity protocols
- Neglect of modern technology for protection such as firewalls
- Omission of network access regulations
- Lack of adequate incident response protocols

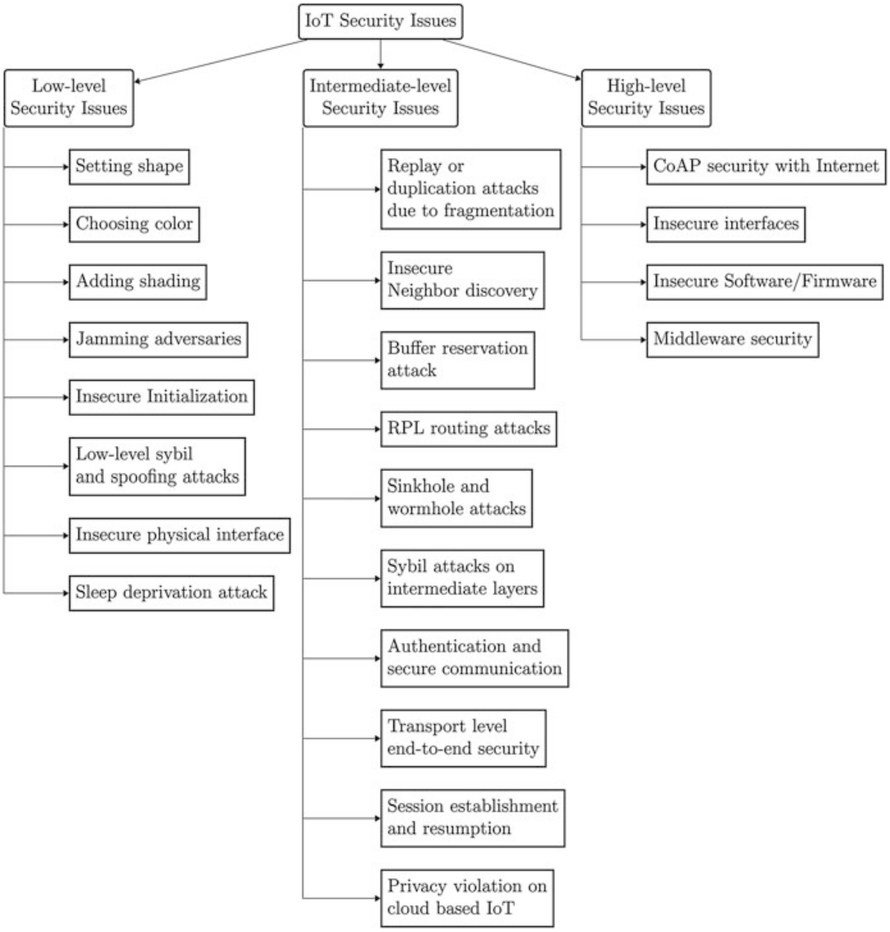

Fig. 10.1 Security issues in IoT [44]

In sustainability IoT, both the device and data security are of vital importance. Different security issues in IoT are shown in Fig. 10.1.

Device security deals with protecting IoT devices from attacks, whereas the data security is related to protection of data integrity and confidentiality being generated from IoT sensors and other monitoring instrument. This also applies to the user privacy. The first step towards the securing IoT devices is risk identification and categorization, in which the impact of different IoT devices is considered. A three-pronged stratagem can be employed to identify risks, which include utilitarian, feasible, and verifiable. The first prong follows the utilitarian principle to identify the practical importance and appropriateness of risk. Then feasibility principle analyses the implementation complexity, cost, and verifiable details which deals with the implementation verifiability. In this process, both

sustainability IoT functionality and cybersecurity needs are considered (device usage and management, configurations, networking capabilities, nature of data collection storage, access and actuation capacity). These risk identification and categorization includes [29]:

- A major factor for sustainability IoT risk categorization is consideration of things based on their information related capabilities [29]. The sustainability IoT can be characterized into active and passive. The examples of the passive devices, which have no actuation capability, include water pH and nutrients sensors, in sustainable water IoT, soil moisture sensor in sustainable agriculture IoT. The active things collect data and also act as actuator to make changes in the physical world. The examples of active things include center pivot systems controllers based on soil moisture sensing which are used in sensor-guided irrigation management systems and also in reservoir monitoring for flow control in dams.
- The physical accessibility of sustainability IoT is considered to establish the risk category. For example, underground soil sensors for monitoring physical, chemical, and biological properties of soil in decision agriculture are hard to locate, access, and excavate. Similarly, sensors in ocean floors, rivers, and other water bodies, in urban underground infrastructure, and mines are difficult to access. The remote access and authentication features should also be identified.
- The communication capabilities of these devices from short range to very long-range communications using different mediums such as central offices wire line, wireless, cellular networks, cable and broadcasting systems, and satellite communications should also be considered for risk categorization. Each of these communication mediums present diverse challenges in terms of risk identification. Moreover, the types and duration of data collection transmission should be analyzed to characterize risks.
- The power source and energy efficiency are vital for sustainability IoT risk characterization. The things can be either battery powered or hard wired. Accordingly, energy harvesting mechanism and power transfer mechanism to enhance battery life should also be considered [37].
- The IoT authentication capabilities, device software graduation, and patching approaches are also used to determine risks. It includes system and network authentication and device access identification. The personally identifiable information (PII) poses high risks [95].
- The sustainability IoT firmware and software modules complexity and configuration are also fundamental components of the risk identification and categorization [18].

Accordingly, based on sustainability IoT risk categorization, the risk mitigation goals and areas are defined based on the significance of the risks categorization identified in the first step. These risk mitigation challenges, recommendations in different areas are discussed in the following [16, 67]:

- To prevent unauthorized access to system, adequate logical and physical access procedures should be instituted using the state-of-the-art authentication mechanisms. Moreover, all access and use of resources by anyone should be logged properly for proactive avoidance.
- For the purpose of efficient management of cybersecurity risks, a database should be maintained for IoT and their operational characteristics (firmware version, services, functionalities, and software version) as discussed above. This should also include all relevant information about the device status.
- Keeping track of software and hardware vulnerabilities is useful to reduce exposure of system to digital attacks. Accordingly, these vulnerabilities can be fixed by employing a systematic approach.
- The data generated from all phases of sustainability IoT life cycle should be protected at all stages during sensing, collection, transmission, analysis, and visualization from manipulation and compromise by using best cryptography and security practices.
- A continuous monitoring of data and devices is important to identify any incidents of data and security breaches, vulnerabilities, and bugs.

The next step in securing sustainability IoT paradigm after identification of cybersecurity goals and areas is implementation of these goals (also called the cybersecurity feature implementation). This process is performed considering the technical specifications of sustainability things (e.g., hardware needed to support a particular feature keeping in view the current in future needs). The emphasis is on hardware based feature implementation because of efficiency and use of some of the existing built-in features in the devices. A cybersecurity risk management roadmap is shown in Fig. 10.2. In this process, system performance is also monitored to identify any adverse impacts of the features. The adoption of a system level approach has tremendous potential where all elements of the sustainability IoT are considered such wireless communications and interaction with other things. For example, precision agriculture cybersecurity features should be implemented considering all farm equipment and privacy issues [1].

There are many common security vulnerabilities that go unnoticed during development and shipment phase. The update related issues that are generally observed include user/devices never getting an update (inability in terms of device capabilities), failure of the vendor to send updates (due to absence of autonomous sending patches and updates), and users failure to apply updates.

Moreover in the absence of adequate authentication and encryption mechanisms in place, the update and patch push approach is unlikely to be successful because of security issues and devices can be compromised. Moreover, data theft issue can happen at unsecured device (no or plain text passwords), cloud (man in the middle attack), and network communications levels (no encryption) The detailed IoT security considerations at different levels are outlines in the following:

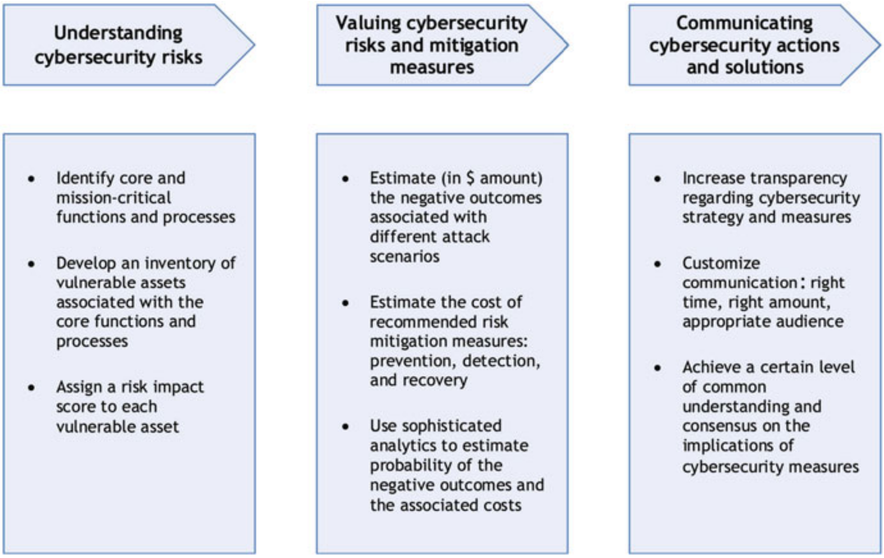

Fig. 10.2 A cybersecurity risk management road map

- At data and application layers in IoT Applications: It includes malware, theft of data, unauthorized access, man-in-the-middle attacks, unauthorized software, spoofing, fraud, denial of service, and inconsistent software versions.
- At networking level: It includes denial of service, spoofing, protocol tampering, hijacking, clear text communications, false base station, man-in-the-middle attacks, and lack of monitoring.
- At device level: It includes back doors and call home functions, reverse engineering, unauthorized software, side channel, device cloning, proxy acts, and resource limitation.

10.1.1 IoT Security Principles

The U.S. Department of Homeland Security in its report Strategic Principles For Securing The Internet Of Things (IoT) has defined following principles to address IoT security challenges [25]:

- Incorporate Security at the Design Phase
- Advance Security Updates and Vulnerability Management
- Build on Proven Security Practices
- Prioritize Security Measures According to Potential Impact
- Promote Transparency across IoT
- Connect Carefully and Deliberately

10.1.2 Digital Forensics in Sustainability IoT

The digital forensics in sustainability IoT deals with the investigation of data on IoT and digital devices related to legal matters and computer crime. Currently, there is no standard set of guidance for data retrieval for the purpose of the litigation investigation in case of cyber comprise, theft, or other crimes. To meet this requirement, there is a need for collaboration to cyber, digital, computer, and network forensics experts, industry, and government authorities.

10.2 Openness Paradox and Data Dichotomy: Privacy and Sharing

In sustainability IoT, data collected at large spatial, temporal, and environmental scales carries a huge economic value. The openness and data flow are of vital importance for decision support systems and for developing sound data driven practices, and at the same time requires protection as well [31]. In this section, the challenges of data sharing and privacy in sustainable IoT are discussed in detail.

10.2.1 Privacy in Sustainability IoT

The identification of privacy regime and concerns is important in sustainability IoT due to the sensitive nature data in sustainability IoT. Due to its large-scale sensing and data monitoring capabilities, the enormousness amount of data is being generated in different paradigms such as climate, water, energy, and health. In this regard, the data privacy and protection is being considered pivotal for successful functionality of the system. However, different IoT generate different amount of data. One big motivation for protecting data is to avert users data being revealed and to block circulation of protected information. For the first case, well-designed sifting approaches can be used to curb revealing individual information. For proprietary information, formation of proper training is vital to protect dissemination of the data.

10.2.1.1 Data Sifting

Data sifting is an important privacy mechanism to ensure privacy and achieves balance between the scenarios of no data sharing at all and everything being shared. This approach also ensures that the important information and data about climate change, water, and health related issues while protecting the privacy of individuals

(e.g., age, name, address, location, and social security numbers). However, by removing this information entirely makes gender, age, and location based analysis impossible to conduct.

Another important privacy achieving mechanism also called the differential privacy includes adding a well calculated noise to the aggregated understudy data set such that results are twisted to make identification of the individuals difficult. In this approach, the exact data is replaced with range and data granularity is reduced statistics based data summarization. The quantity and quality of noise depends on the size of data set being analyzed. Accordingly, machine learning [15] can be used for data mining and to construct models from the data. An aggregation approach is shown in Fig. 10.3.

10.2.1.2 Proxy Data Analyzer

In this approach, intelligent proxy data analyzers are used to process data based on the data request. This approach enables selective data sharing across different domains based on metadata, data sensitivity, and previous requests. Using proxy data analyzer, multiple sustainability IoT data sets can be combined to regional to universal planning. The FLEX is an example of proxy data analyzer that provides differential results by using a set of precomputed data metric. These privacy-preserving approaches will enhance end user trust in system, hence removing barriers in technology adaption by encouraging innovation.

10.2.1.3 Multi-Layered Approach to Privacy

In a multi-layer approach to protect privacy in sustainability IoT paradigm, each layer can guard against the specific set of data being reveled. For example, data element encryption added an additional layer of protection. Similarly, at the session and presentation layers, use of encryption mechanisms is useful to mitigate attacks conducted during data communications. In summary, the strong privacy protections will be helpful to advance the sustainability IoT paradigm.

10.2.2 Universal Data Flow, Sharing, and Standardization

The open flow of data and sharing coupled with best management practices brings tremendous value to sustainability IoT and is the lifeline of the entire ecosystem. The design of new data sharing platforms for sustainability has the potential to bring robust policy planning and decision making in different areas such as environment.

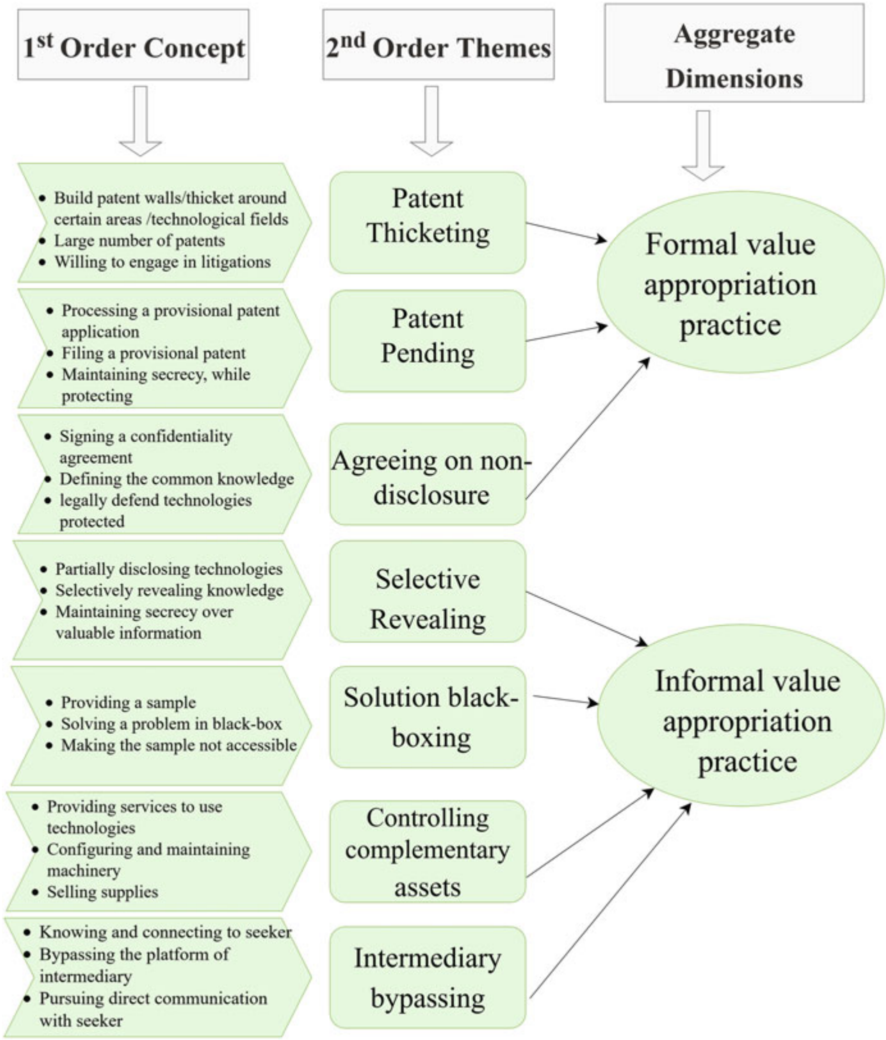

Fig. 10.3 An analytical aggregation approach [31]

10.2.2.1 Significance of Data Sharing

The data localization inhibits global scale mitigation, cross-border forecasting, and planning efforts, whereas more socioeconomic and environmental benefits can be realized by global sharing. For example, in energy sector, loads can be identified and proper system planning can be done. Similarly, in health sector, the underlying causes of spread of a particular disease in affected communities can be established, which will also be beneficial for world population at large to prevent disease outbreak. In transportation, better public services can be designed. Similarly, the

availability of timely and certain data has a vital role to play in improving the urban underground infrastructure monitoring. It can also facilitate the development of monitoring systems for sewer and storm water overflows through real-time operation. The data localization also presents a barrier to international adoption of different sustainability IoT paradigms. In this regard an establishment of a global cloud for sustainable IoT will be good step in the right direction. The data flow and sharing can be conducted at two levels.

- At strategic level (community and large geographical level): to give certain pertinent data about the community to policy makers for analysis and strategic decision making
- At tactical level: for local operation, planning and forecasting and behavior identification to understand and address the societal, social, and environmental issues and challenges.

10.2.2.2 Data Standardization

The deployment of sustainability IoT devices in different infrastructures with multitude of sensors and instruments provide many tremendous avenues for valuable data collection. The data collection from different sustainability IoT can be classified into (1) exhaust, (2) sensing, (3) crowdsourcing, and (4) web-based. However, different schematics and data access procedures, variations in data storage formats, difference in spatial and temporal granularity present big challenges in combining, comparison, analysis, and interpretations of these data sets.

The data standardization deals with data storage and management using reliable mechanisms in structured format to enable large-scale data analytics. The availability of structured data makes it extremely easy to make futuristic predictions. Accordingly, advanced data analytics can be used to predict, estimate, diagnose, and prognose events and outcomes from past and current data flows in real time. It also enables a consistent aggregation of data across different sources and places. Accordingly data-driven and analytical models can be developed in different areas related to sustainability (e.g., renewable energy profiles, weather forecasting, water monitoring planning, and analysis for sustainable community development).

10.3 Opportunities and Challenges in IoT for Sustainability

The IoT has strong potential to transform different sustainability areas using sensing and communications technology. It is capable of effectively responding to the current environmental, energy, water, and health challenges using the technology and hence can achieve the sustainability goals and bring improvements to quality of life. Its sensing and monitoring brings benefits to the society by fixing environmental issues, and also guides regulations and policy making. For example, sensors in

water bodies are used to obtain useful information about the quality and flow of water, which helps in waste and treatment management. Similarly, soil sensors provide useful information about the physical, chemical, and biological proprieties of the soil which aids in improving crop yield and water resource conservation. Yet, bountifulness of these opportunists comes with many challenges at the technical level and policy level. These challenges are discussed in the following section.

10.3.1 Technical Challenges

The challenges in IoT for sustainability are:

- Sustainability Data management. Novel approaches are needed for data collection, storage, sharing, and analysis due to size, scale, and distributed nature
- In privacy and cybersecurity, and equitable access regarding exposure, manipulation, and misuse of critical data
- Lack of encryption, resources for a certain level of protection, privacy guidelines, and protection against malicious cyberattacks
- Sustainability device homogeneity increases vulnerability of cascading and repetitive attacks
- Existing public infrastructure compatibility and integration issues. Lack of interoperability (at network, system, and data formatting levels) causes data silos, redundancy, and inefficiency

10.3.2 Policy Challenges

Smart global and national strategy for public regulations and policies, based on environmental, social, and economic factors are critical for the success of sustainability IoT to deal with huge challenges in meeting sustainable development goals. The policies developed using collaboration and civic engagement will have strong impact on sustainability. The policy level challenges and sustainable actions recommendations are discussed in the following section.

- Need of inclusive collaboration and civic engagement planning among different sectors keeping in view the current and future needs. For example, sensing in one area has the potential to meet the needs of other area too (e.g., carbon dioxide emissions in energy, climate, and transportation). In this regard engagement with public, academia, and private industry is also of vital importance to develop and deploy the state-of-the-art technologies.
- Community engagement should also be focused on people participation and citizen engagement. The sustainability things will be useless and wastage of resources and other infrastructure if citizens are unable to use the system. In this regard, providing access and expansion of services to rural broadband

will certainly increase access to these systems. The constituency resources and demographics are of fundamental importance for the planning and deployment purpose.
- Policies for data access, ownership, and stewardship.
- Policies to mitigate behavior change resulting from the deployments of sustainably IoT systems.
- Development of trust and reliability frameworks.

10.4 Progress in IoT Security Standardization

The full potential of sustainability IoT will be realized only if it operates in an open and secure environment. Different security groups and industry are developing technology and security standards to promote interoperability, and to encourage open and secure cross-border data communications. The different technology and security groups for IoT and their standardization efforts are discussed in Table 10.1 [98].

10.5 Case Studies

In this section, different sustainability IoT cybersecurity case studies are discussed. First, the case study of cybersecurity and data privacy in digital agriculture is presented.

10.5.1 Cybersecurity and Data Privacy in Digital Agriculture

The digital agriculture has been envisaged as a novel archetype to transform present-day agricultural practices by real-time sensing, processing, and collection of data for the purpose of developing efficient seeding and irrigation techniques, fertilizer applications, and other farm operations [3, 9, 27, 36, 52, 70–78, 80, 82–87, 93, 96]. Many security threats are emerging in the nascent field of digital agriculture (also referred to as decision agriculture and precision). In digital agriculture, various types of sensing and communication technologies are used (e.g., in situ sensing, remote sensing, machine learning, and data analytics.) Hitherto, the agriculture field was dependent on mechanical device and technology use was minimal. Accordingly, by using these networked technologies for sensing and data collection, different types of field inputs such as water for irrigation, fertilizer, and pesticides can be applied precisely in agricultural farms that improve efficiency, bring enhancements in crop yield, and lower costs. However, with this rapid growth of agricultural technologies, there is corresponding increase in vulnerabilities. In this section, we discuss those vulnerabilities, prospective threats, and solutions.

Table 10.1 The IoT technology and security standard developments activities [98]

Organization	Description
IoT Cybersecurity Alliance	A group of industry leading cybersecurity and IoT experts to help address the challenges that exist across the IoT ecosystem
Cloud Security Alliance	Best practices and research
Alliance for Internet of Things Innovation	It aims to strengthen the dialogue and interaction among Internet of Things (IoT) players in Europe, and to contribute to the creation of a dynamic European IoT ecosystem to speed up the take up of IoT.
Broadband Forum	A non-profit industry consortium dedicated to developing broadband network
European Telecommunications Standards Institute (ETSI)	Produce applicable standards for ICT-enabled systems, applications and services deployed across all sectors of industry and society
GSMA IoT Security Guidelines	It include 85 detailed recommendations for the secure design, development, and deployment of IoT services that cover networks as well as service and endpoint ecosystems. It addresses security challenges, attack models, and risk assessments while providing several worked examples.
IEEE Internet of Things	Security and Encryption Standards. IoT security issues and vulnerability.
Industrial Automation and Control System Security	It develops security standards and technical reports.
Industrial Internet Consortium (IIC)	Security-related architectures, designs and technologies.
International Electrotechnical Commission (IEC)	International Standards and Conformity Assessment for all electrical, electronic, and related technologies
International Organization for Standardization (ISO) IoT Standards	Develops standards for security
Internet of Things Consortium	IoTC is a non-profit member based organization connecting a global ecosystem of leading companies building the Internet of Things
IoT Security Foundation	IoTSF is a collaborative, non-profit, international response to the complex challenges posed by security in the expansive hyperconnected world
ITU-T SG20	An emerging standard
National Institute of Standards and Technology	CPS PWG cyber-physical systems (CPS) framework, and NIST cybersecurity for IoT program
North American Electric Reliability Corp	Responsible for reliability and security of the bulk power system in North America
oneM2M	It is a global standards for machine to machine communications and the Internet of Things.
Online Trust Alliance	OTA is convener of a multi-stakeholder initiative to address public policy and technology issues impacting IoT devices.

(continued)

Table 10.1 (continued)

Organization	Description
Open Connectivity Foundation	The open connectivity foundation (OCF) is a group of over 300 technology companies, including Cisco, Intel, and Samsung, and is developing interoperability standards for the IoT and sponsoring an open source project to make this possible.
Open Mobile Alliance (OMA)	OMA device management security describes general security requirements, and provides description of transport layer security, application layer security
Open Web Application Security Project	The OWASP Internet of Things project is designed to help manufacturers, developers, and consumers better understand the security issues associated with the Internet of Things, and to enable users in any context to make better security decisions when building, deploying, or assessing IoT technologies.
OpenFog Consortium	Enabling advanced IoT, 5G and AI with fog computing
SAFECode	The software assurance forum for excellence in code (SAFECode) is a non-profit organization dedicated to increasing trust in information and communications technology products and services through the advancement of effective software assurance methods.
Smart grid interoperability panel (SGIP)	SGIP is an industry consortium representing a cross-section of the energy ecosystem focusing on accelerating grid modernization and the energy internet of things through policy, education, and promotion of interoperability and standards to empower customers and enable a sustainable energy future.
Thread Group	Thread was designed with one goal in mind: to create the very best way to connect and control products in the home
The Update Framework (TUF)	The update framework (TUF) helps developers to secure new or existing software update systems, which are often found to be vulnerable to many known attacks.
U.S. Food and Drug Administration (FDA)	Management of postmarket cybersecurity vulnerabilities for marketed and distributed medical devices
US Department of Homeland Security (DHS)	Strategic principles for securing the Internet of Things
3rd Generation Partnership Project (3GPP)	A global initiative that unites seven telecommunications standards development organizations (known as “organizational partners”), the 3GPP develops specifications covering cellular network technologies, including radio access standards.
Internet Engineering Task Force	IoT Standards
CIS Center for Internet Security	CIS is a forward-thinking nonprofit that harnesses the power of a global IT community to safeguard public and private organizations against cyber threats.

It is important to note some of the common threats (e.g., malware, theft of data, unauthorized access, man-in-the-middle attacks, unauthorized software, spoofing, fraud, denial of service, and inconsistent software versions) found in conventional connected systems also pose risks in the field of digital agriculture [28, 69]. Therefore, these can be identified by using the conventional risk characterization approaches discussed in this chapter, and, accordingly the same established risk mitigation can be applied. However, due to distinctive operation of the farm machinery, equipment and underground sensors, vast area of exposure from field to farms, various type of new threats are emerging which were not observed previously with wide range of ramifications. These consequences range from interference to routine field work to total disruption and unavailability of farm operations and compromised integrity and confidentiality of farm data. Moreover, the data leakage and theft negativity impacts the agricultural resiliency and sustainability.

10.5.1.1 Information Privacy in the Field

In digital agriculture, the data privacy is a major issue in relation to technology implementation. Recently, plenty of critical data has been collected by farmers about their farms such as crop yield data which they are reluctant to share due to different factors (e.g., finance, market trends, and soil value) [104, 105]. Across a typical agricultural farm, many variations in soil texture, nutrients, and volumetric water content are observed [76]. The agricultural technology is used in these temporal and spatial variations to ascertain field conditions for variable applications of fertilizer and irrigation in order to maximize yields and profits which provides financial gains to farmers. To determine field conditions for best resource allocation, various technologies (e.g., GPS, GIS, and sensors are being used) where data can be collected and stored in cloud for processing.

Since, at large spatial scales, the soil texture and rain data is highly correlated, the cloud data collected from multiple farms can be utilized for decision support systems at regional levels. For example, soil moisture data along with temperature across different farms can be used to inform irrigation decisions [27]. Consequently, with this benefit, the data privacy becomes a concern particularity in geo-spatial usage of privacy information [20]. For the reason that location data is used by vendors, dealers, and digital agriculture service and equipment providers for developing analytics, improving service and for creation of new business models; the security threats and attacks make the farmers data exposed and vulnerable.

Such security breaches are detrimental as not only the farm's equipment and sensing data is revealed, the other proprietary information is laid bare such as irrigation cycles conducted in a typical growing seasons, software design and version, seeding approaches, and yields. Since, the success of the farming depends on these, therefore, the farmers keep these information confidential. Currently, in the developing area there is dearth of mechanisms to protect data privacy [49]. One privacy protection mechanism that has applications in this area is obfuscation

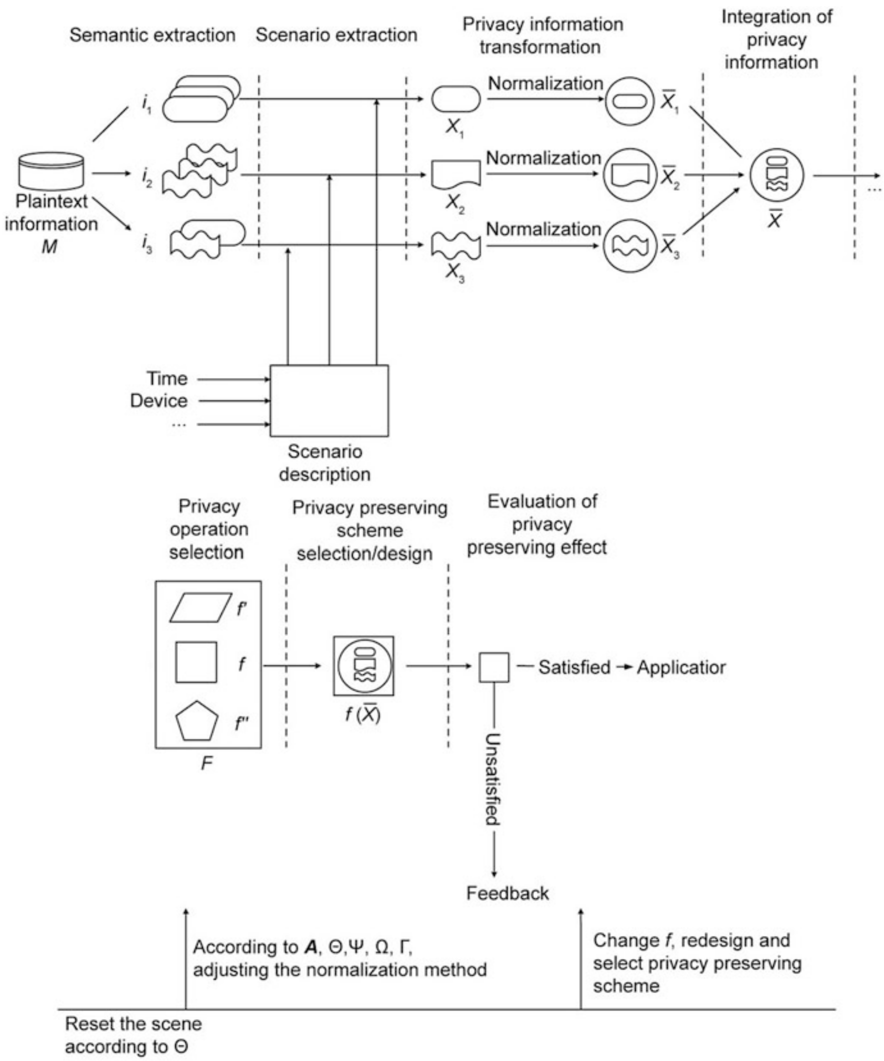

Fig. 10.4 A privacy computing framework [49]

(see Fig. 10.4) where exact location information is replaced with confusing and ambiguous information. However, this will render geographic services unable to function because of lack of true data. Moreover, the obfuscation techniques are also vulnerable to the location deduction attacks. Thus, in digital agriculture, advanced mechanisms to protect privacy and location information without surrendering the location information are needed.

Farm data privacy related threats in digital agriculture are discussed in the following [30, 105]:

- Deliberate stealing or unintended leakage of farmers information from decision making systems and other agricultural information management systems to third parties. This targets mobile and tablet apps on the farm equipment and farmers phones. Currently, these applications lack update features and privacy protection mechanisms [91, 105].
- The purposeful publicizing of information to harm a company's reputation and sow mistrust about technology in farmers' minds leads to hindrances in adaption of decision agriculture [105].
- The exploitative trading of confidential data, where companies are approached to sell farmers data in return for some incentives [34].

10.5.1.2 Data Usability in the Field

In digital agriculture, sensors are being used for condition monitoring and real-time decision making at different temporal and spatial scales that cause data consistency issues. These challenges are discussed in the following [75]:

- Publishing of false data about crop disease or other related agriculture to create fears among farmers [69, 105].
- Injection of false data into the sensing networks to create false alarms or trigger harmful actuation such as over irrigation and under irrigation [80, 88].
- Inefficient control algorithms for farm machinery and other in-field equipment.

10.5.1.3 Farm Equipment and Data Availability in the Field

Because agricultural farm operations are heavily dependent on the farm equipment therefore, the data loss is the major challenge in the field. In this major disruptions to the availability are:

- There are some critical time windows in every crop where the of equipment usage is at its peak such as combines in the harvesting systems, center pivot, seeders during planting season, and drip irrigation systems in long dry weather or short-term droughts. Loss or malfunction of equipment during these intervals is detrimental to the crop health. It can also cause crop yield reduction leading to the financial loss to farmers. Attacks conducted to exploit vulnerabilities in the equipment can cause large-scale food shortage and harm the vendors reputation [6].
- The overcrowding of wireless spectrum can cause disruptions to the wireless systems and GPS signals in the agricultural farms. The overcrowding of the spectrum can also lead to improper and unpredictable functionality of the system.

The Federal Communication Chart (FCC) has permitted the use of the cognitive radio devices in the spectrum range of 470 to 698 MHz on farm machinery and agricultural equipment for digital agriculture applications [79].
- The limited availability of rural broadband leads to loss of data, slow data rate, maintenance downtime, and frequent service outages. The wireless communications can also be used to exploit the data being transferred in plain text [61].

10.5.1.4 Cybersecurity Recommendations for Precision Agriculture

Some important recommendations for protection of precision agriculture systems in the field are discussed in the following [17, 51, 103]:

- Security of applications and software being used in the field on farm equipment can be achieved using latest updates, patches, and security mechanisms [92]
- Blocking of communication loopholes by using strong encryption standards for data transfer, and blocking services and protocols not required for device functionality. The implementation of the latest security standards will also reduce risks [12]
- An updated record of device functionality, software, and current status. The continuous monitoring and logging of the device access to verify authorized users. Understanding of data ownership, protection, and recovery protocols is also useful to develop proper incident response strategy

10.5.2 Smart Grid

In modern smart grid systems disruptions in one system can lead to cascading effects in the entire power system [40]. The cyberattacks in grid can cause substantial losses. There is strong need to increase the reliability of these systems by protecting them from cyberattack by incorporating the cybersecurity in the design process. This can be achieved through development of reference security architecture. An example of cybersecurity architecture for the power grid is shown in Fig. 10.5. The design of the next generation power grid system including renewable energy systems can benefit from this which is based on the IP networking.

10.5.3 Health and Cybersecurity

The cybersecurity vulnerabilities and threats can affect the availability of critical lifesaving medical equipment and data. The cybersecurity threats can cause physical impact in patients, hinder the regular hospital operation leaving them unable to provide care [14, 35]. Therefore, attaining the highest level of cybersecurity in

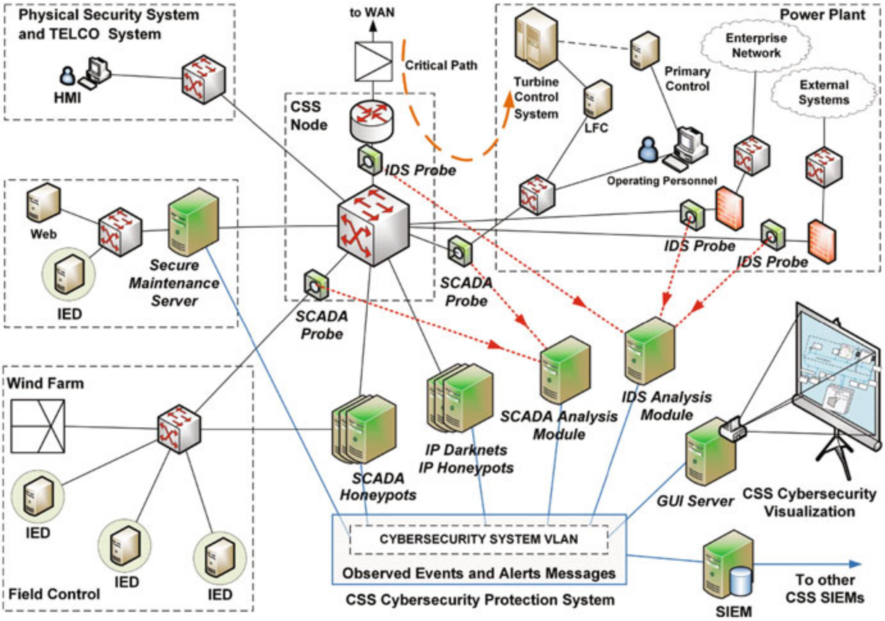

Fig. 10.5 A power grid control system and the designed cybersecurity protection system [40]

healthcare is important for patient safety. The identity theft, ransomware, and targeted patient hacking are some of the vulnerabilities. Other issues are addressed in the following section.

10.5.3.1 Critical Conditions of the Healthcare Cybersecurity

The challenges being faced by the healthcare industry in the area of cybersecurity are discussed below [14]:

- Healthcare industry is facing lack of expert security professionals.
- The legacy equipment is either old or unsupported and contains vulnerable operating systems. The funding dearth allows unsupported equipment to continue functioning.
- The network design is focused heavily on hyper connectivity with less focus on security [32]
- The patient care outage incidents such as locking by ransomware are serious threats to healthcare industry [11]
- Unwillingness to address known vulnerabilities [42]

10.5.3.2 Healthcare Cybersecurity Objectives

The health care security objectives for different patient safety aspects are [1, 22, 35, 66]:

- Confidentiality. The protection of patient information from unauthorized disclosure and access [60].
- Integrity. The protection of patient safety from unauthorized modification of the adequate use of the medical device [102]. It includes the unauthorized access and modification of patient identifiable information including protected health data. The safety of patients' systems from malicious unauthentic actuation, protection of patient physiological data modifications to ensure correct functionality of the software (e.g., processing and algorithmic capabilities) particularly in the monitoring and treatment components of the system are of critical importance.
- Availability. Ensuring the availability of patient information and medical equipment to authorized entities on need basis [50]. It includes rapid updates, secure and authenticated patches, and updates to the equipment, and correct usage of the device for the right purpose thus ensuring and maximizing optimum functionality.

Therefore, continuing cybersecurity risk management is important to use secure state-of-the-art technology [108] to safeguard medical devices and their updates [41]. Some potential cases of risks in the connected medical systems are shown in Fig. 10.6.

10.5.4 Smart Meter

A smart meter is used for electricity usage monitoring. It is used to transmit data to service providers using various types of communication links where this information is used for customer billing, load balancing, energy consumption analysis, and price optimization. The cybersecurity threats related to the smart grids and meters include [39, 45, 46, 62, 97, 97, 107]:

- Malicious attack to disconnect utilities service resulting in loss of power [94]
- Coordinated cascading network attacks on grids, using compromised meters [24]
- Theft and break-in planning when the home owner is away based on the analysis of energy usage [55]
- Denial of service attacks where legitimate requests by the utility service provider are rejected [13]
- Data injection attack to produce invalid measurements of energy consumption [5]
- Smart metering privacy compromising attacks and man in the middle attacks [68]

Fig. 10.6 A list of healthcare cybersecurity risks

- The meter spoofing, authentication attacks, and disaggregation attacks are some of the other examples [109]

  The smart metering cybersecurity threats are shown in Fig. 10.7.

10.5.5 Water Systems

The fresh water is crucial for life on earth. The water systems face different types of threats such as natural, caused by human activity, disasters, droughts, earthquakes, and terrorism [21, 56, 65].

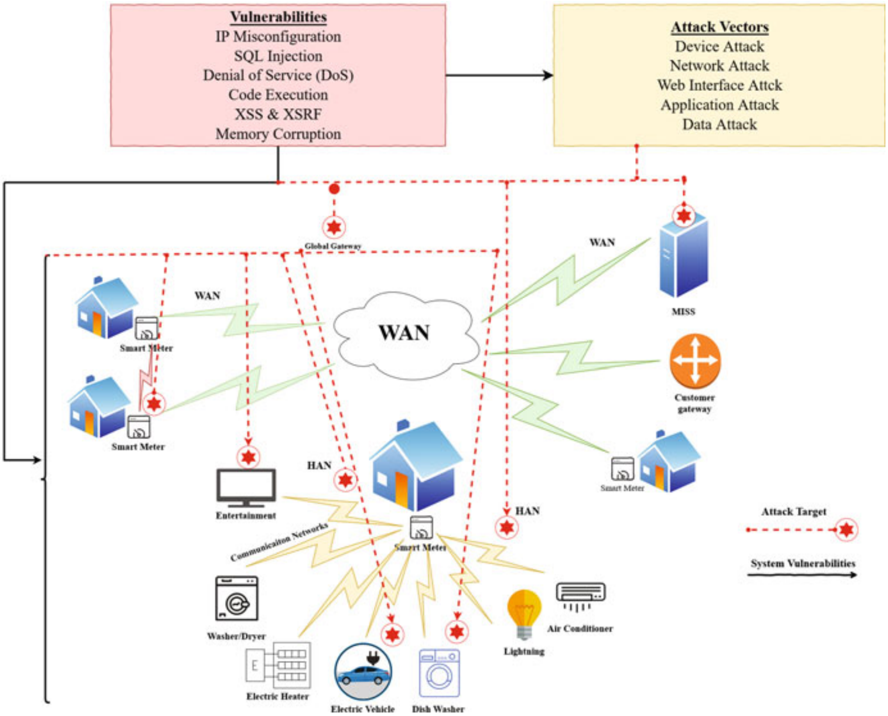

Fig. 10.7 The cybersecurity threats in smart meters [97]

- The contamination attacks and other terrorism related activities, flooding, and storms are the direct threats to these systems [4]
- The water scarcity and lack of water resource availability are also major threats to the sustainability [8]
- Threats of contamination and pollution from point- sources and non-point source and biodiversity loss [48] (see Fig. 10.8.)
- The climate related threats on water [19, 23, 26, 47, 57, 59, 63, 100, 106]

The waters systems security threats can be mitigated by water systems risk characterization, use of sustainable water IoT contamination monitoring and warning systems and through use of advanced machine learning systems for threat modeling [38, 64].

Fig. 10.8 The contamination cycle [99]

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